Simulations of the MU2E beamline and other HZDR contributions

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The FLUKA radiation transport code

- Fully integrated particle physics **Monte Carlo** simulation package (maintained by CERN-INFN)
  - *Current version:* **FLUKA2011.2x.7**
- Historical origin (1970): **FLU**ktuierende **KA**skade (J. Ranft *et al.*, Leipzig)
- Simulation of interaction and transport of about 60 different particles
- Includes treatment of **residual radiation**
- Well tested **built-in scoring**
- Linux platform (g77/gfortran)
- Postprocessing routines for combining results
- Graphical user interface: **FLAIR** (**FL**UKA **A**dvanced **I**nte**r**face)

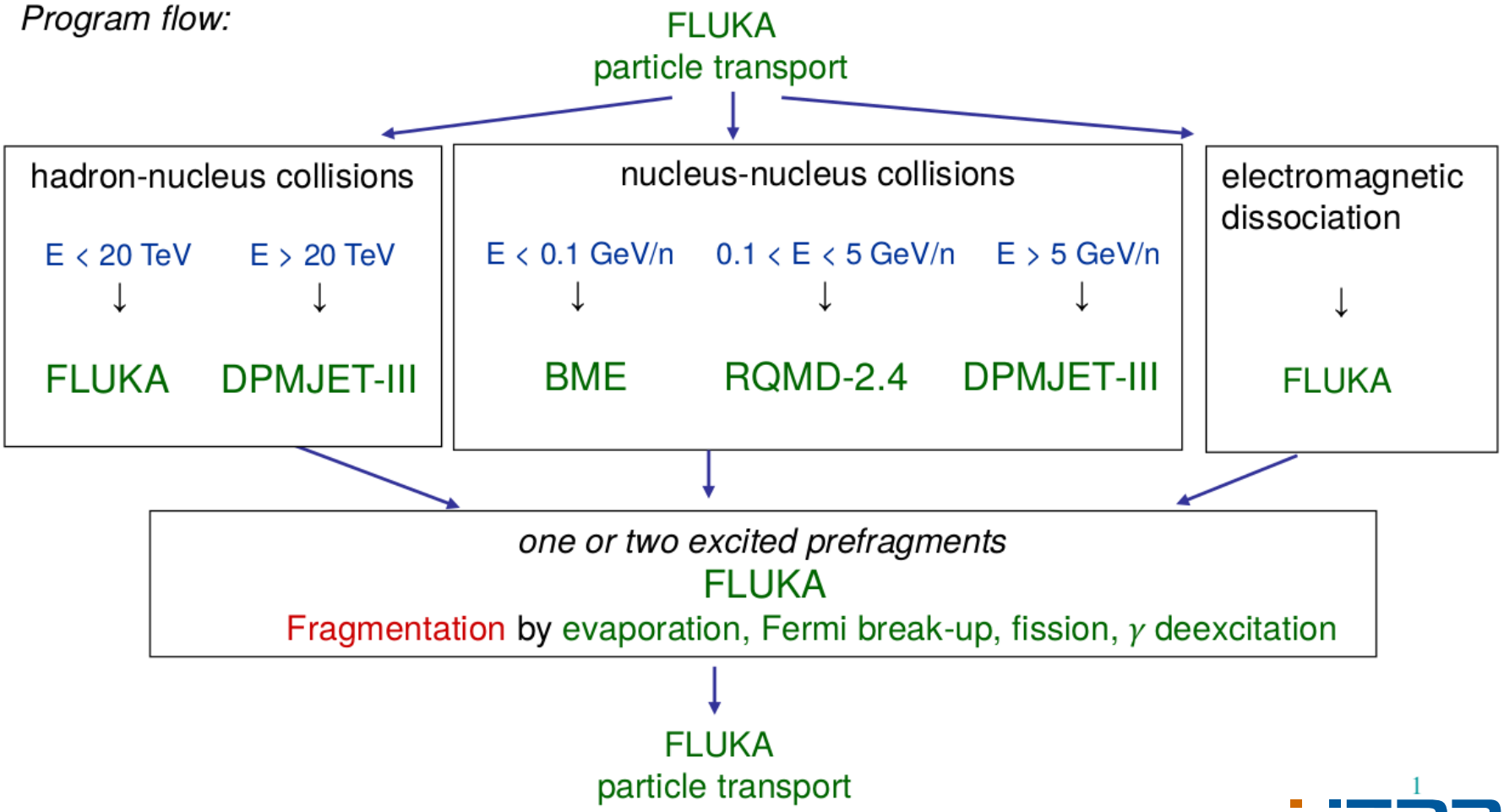
HZDR

Heavy Ion interactions in FLUKA

Models:

DPMJET Dual Parton Model (R.Engel, J.Ranft, S. Roesler)
RQMD Relativistic Quantum Molecular Dynamics Model (H. Sorge et al.)
BME Boltzmann Master Equation theory (E. Gadioli et al.)

Program flow:



Neutrons and low energy neutrons in FLUKA

- Transport and interactions of neutrons with energies < 20 MeV are handled by a dedicated library, while at higher energies interactions are described via the FLUKA nuclear models

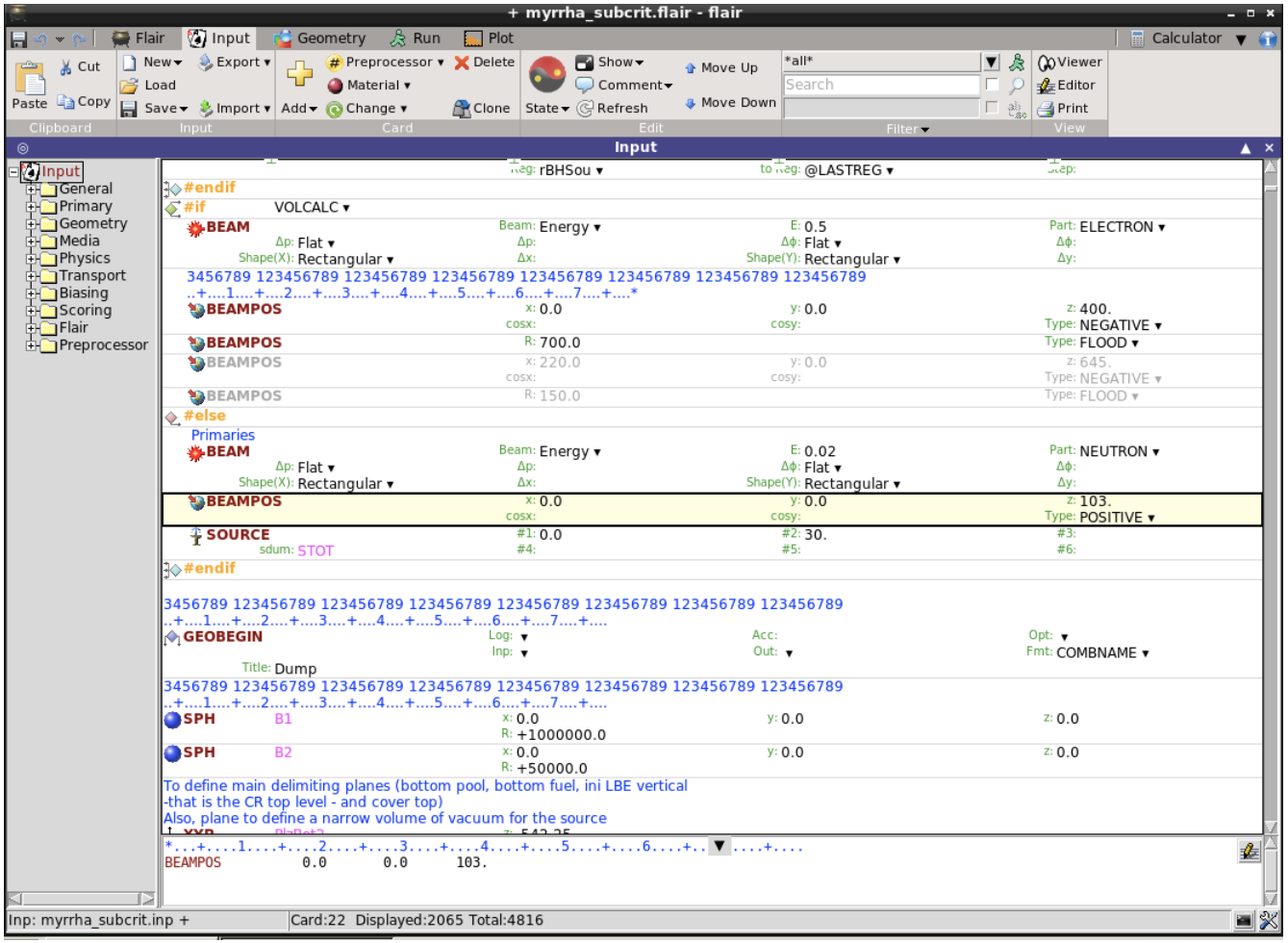
- The low energy neutron library, based on recent version of evaluated data files (ENDF/B-VI.8, ENDF/B-VII.0, Jendl-3.3, Jeff-3.1,..), uses a multigroup approach: elastic and inelastic interactions are not simulated as exclusive processes, but **by a group to group transfer probability (downscattering matrix)**

This kind of treatment cannot be avoided at low energies, because the available cross section evaluations for low-energy neutrons (used by **all codes**) **provide only inclusive cross-sections**, with the secondaries from different reaction channels uncorrelated ➡ in this energy range a complete description of a single event cannot be performed

- Neutrons from (n,xn) reactions are taken into account implicitly by a group-dependent non absorption probability (i.e. a factor by which the weight of a neutron is multiplied after a collision)

FLAIR: FLUKA Advanced Interface

Editor for input file creation



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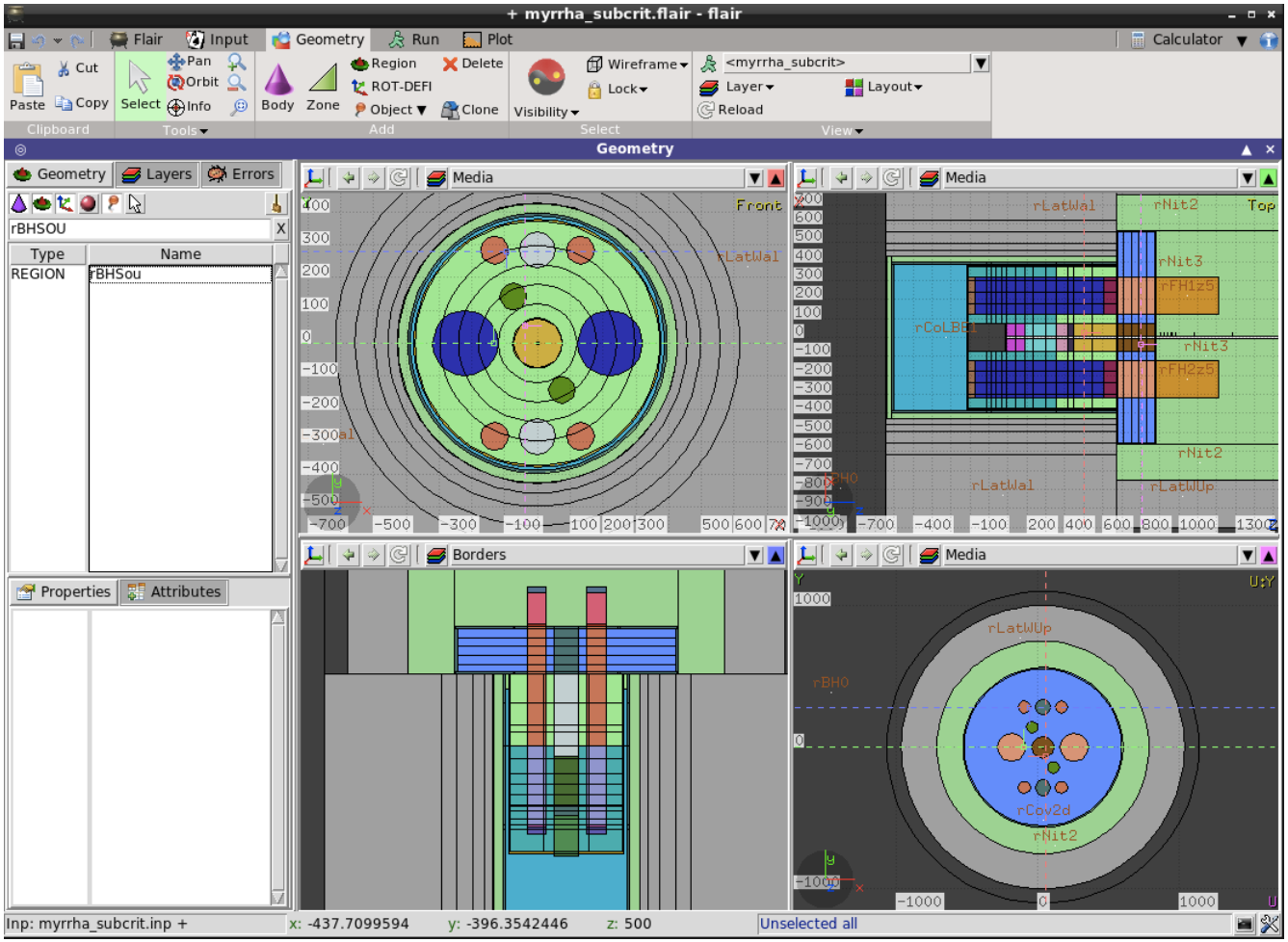
Visualization of geometry



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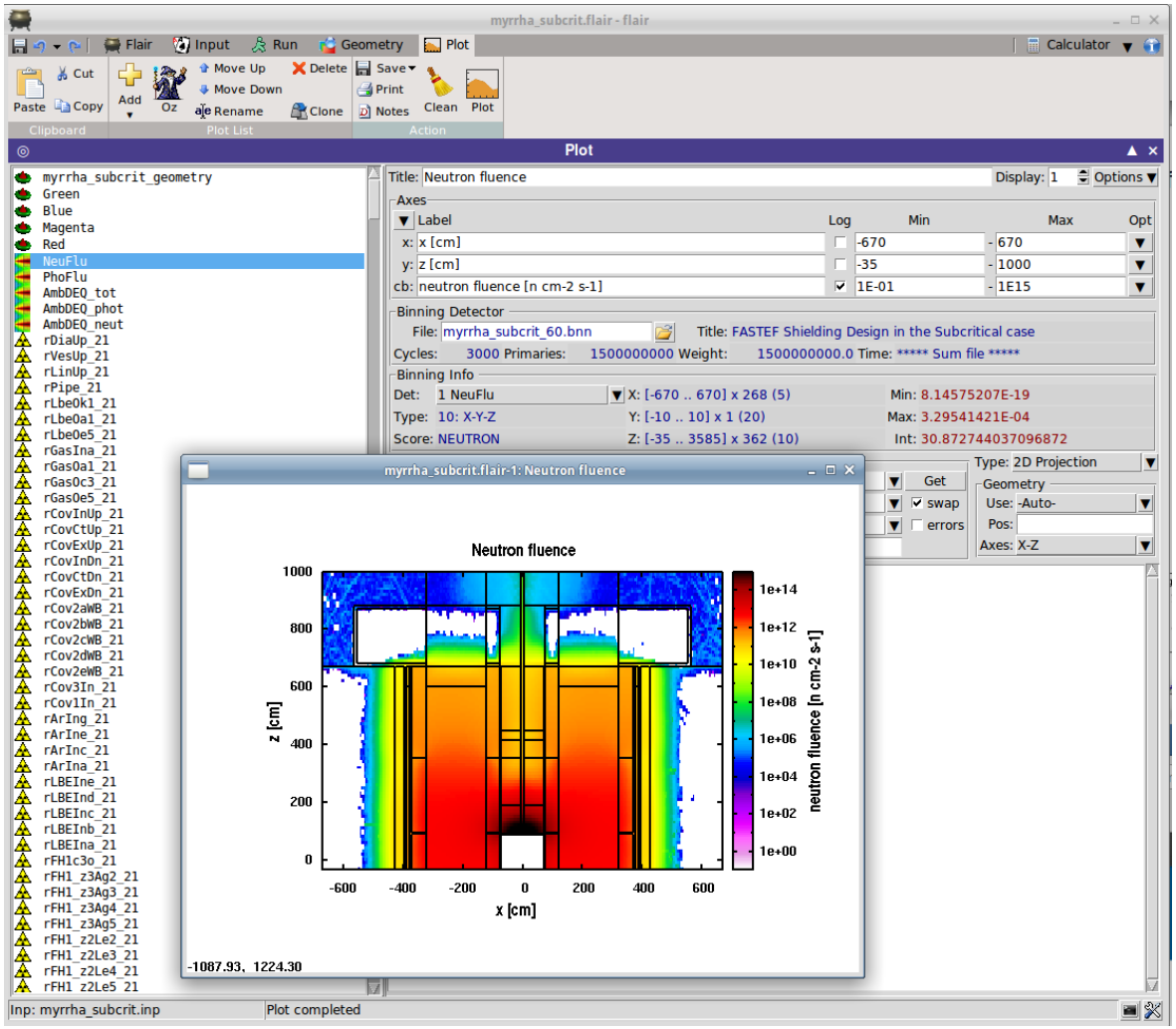
Plotting of results



Plans/Requests for FLUKA studies

Mail from Doug Glenzinski on 28.04.2017:

a) calculate the number of μ- stopping in the aluminum stopping target per proton on target (POT); show their arrival time at the stopping target

b) same, but for π- stopping in the stopping target

c) show the multiplicity and energy spectrum of neutrons originating from the stopping target

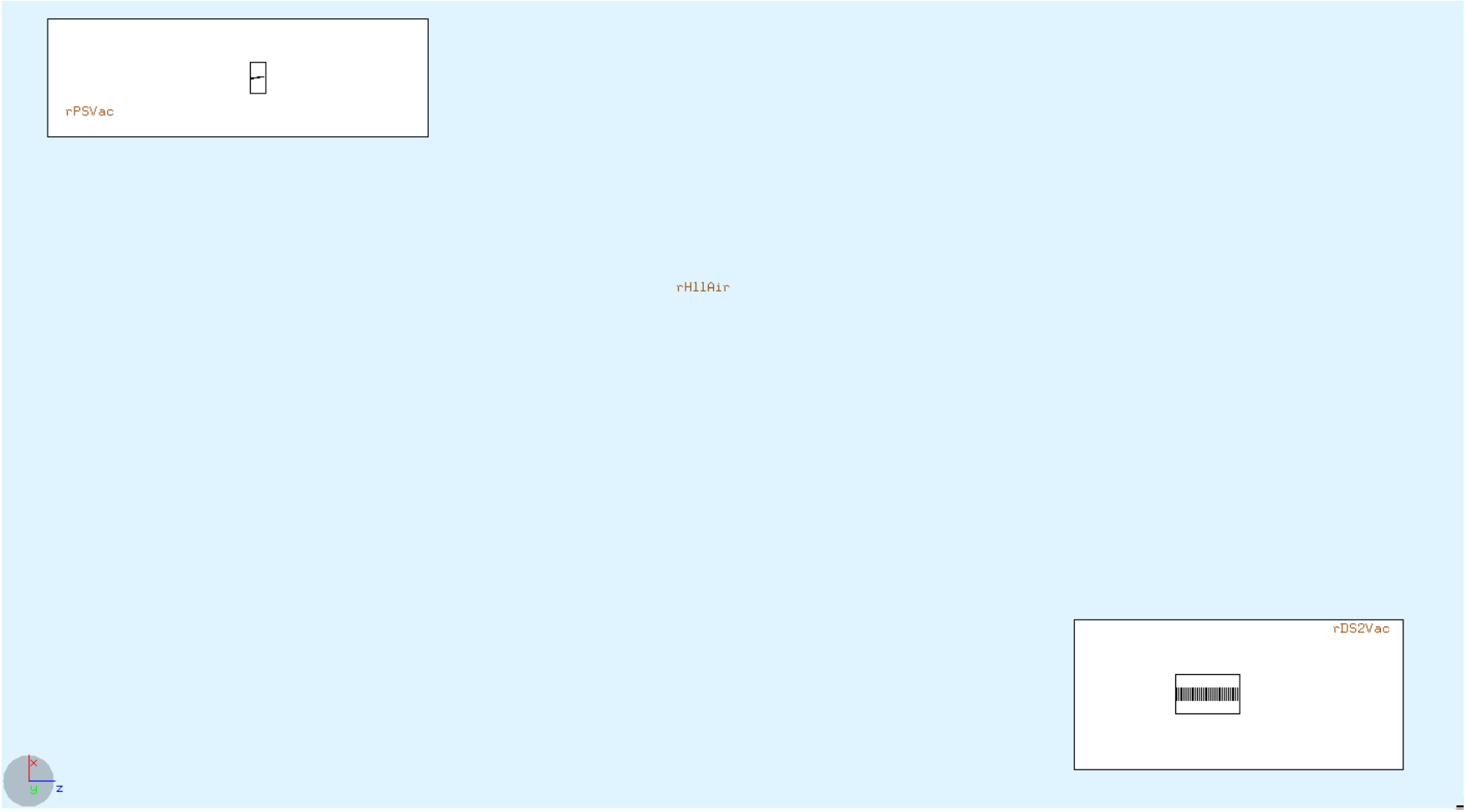
d) show the momentum spectrum and timing spectrum of particles as they enter TS1, exit TS3, exit TS5, and just before they enter the tracker volume (spectra separately for μ-, π-, e-, neutrons, photons, μ+, π, e+)

e) estimates of absorbed dose in various electronic elements and neutron and photon rates at the CRV

f) ...

First steps for MU2E Geometry in 2018

Production Target and Stopping Target modeled with FLUKA



Stopping Target still 34 foils, no holes.

Source terms for the FLUKA simulation

Currently, two source terms defined for the simulaton:

- `SPROT`: Proton beam hitting production target
  - 8 GeV kin. energy
  - Gaussian smearing of position with 1mm sigma
- `SMUST`: Muon beam before stopping target
  - kin. energy sampled from histogram (`..._s1_mubeam_s2_ ...`)
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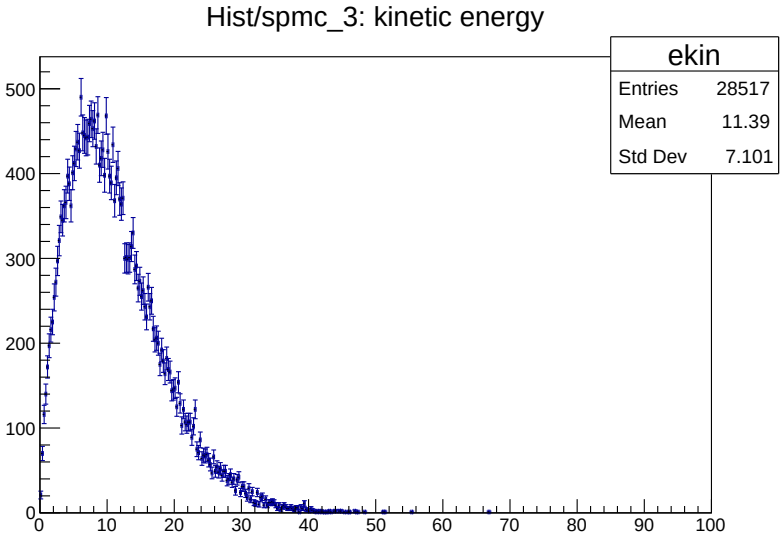

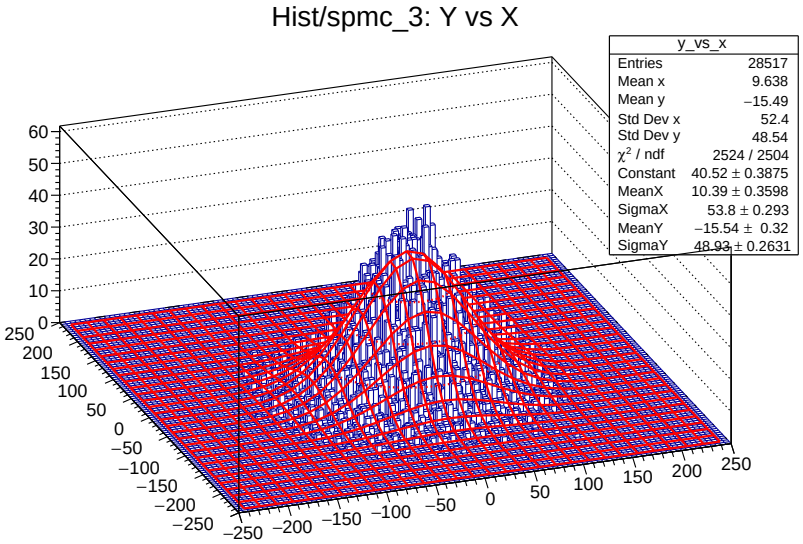

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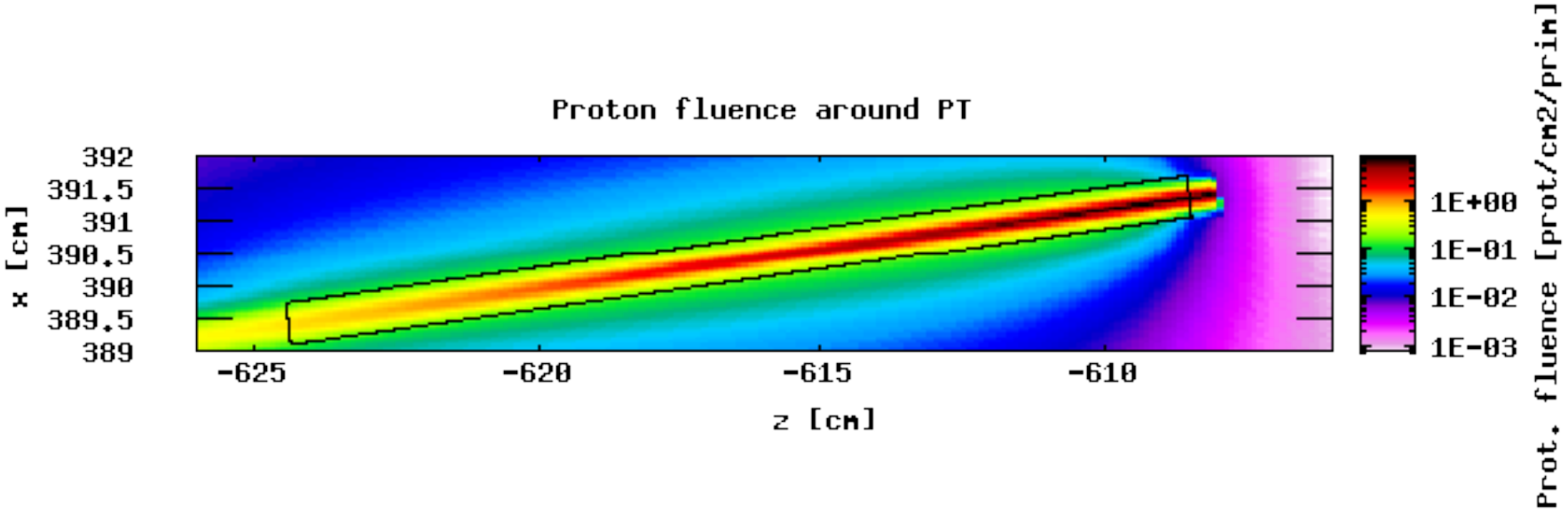

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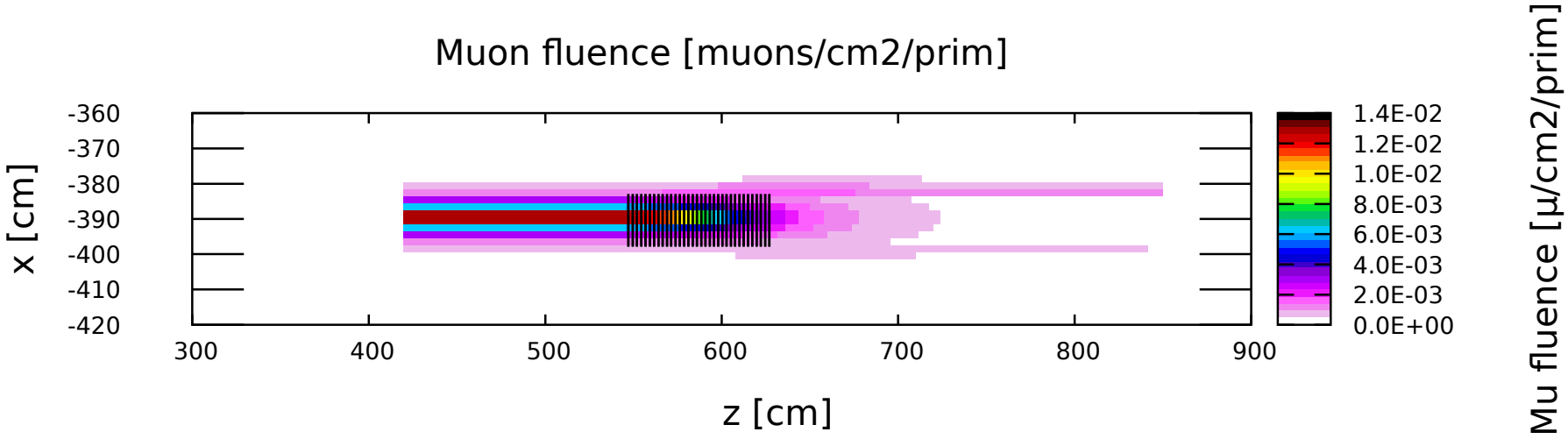

First result: Energy deposition in production target

SPROT source (8 GeV protons, Gaussian smearing 1mm, 12 Mio. POT) on Tungsten target (ϱ =19.3g/cm^3)

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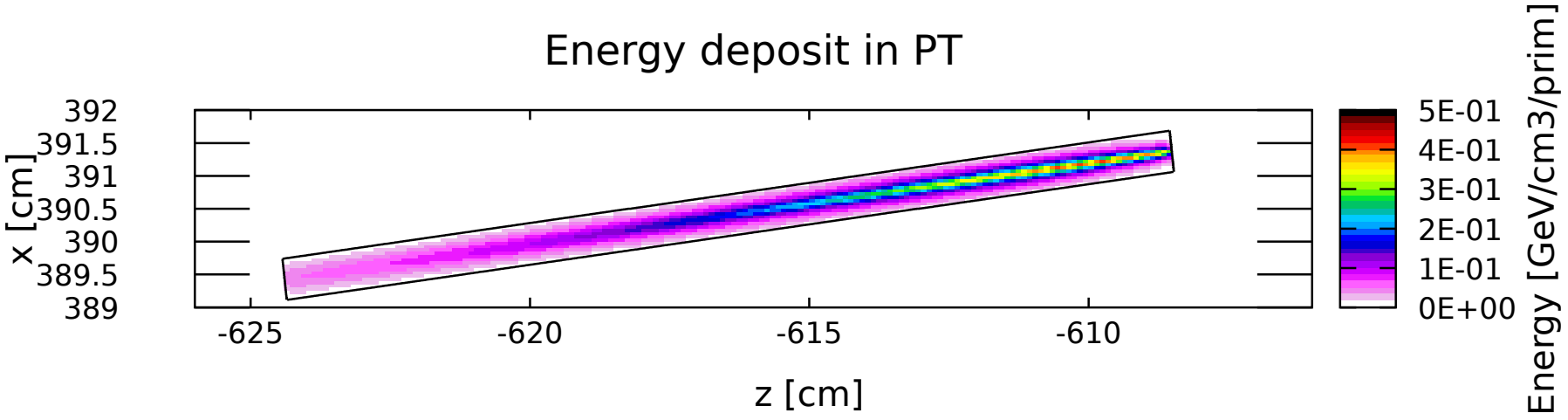

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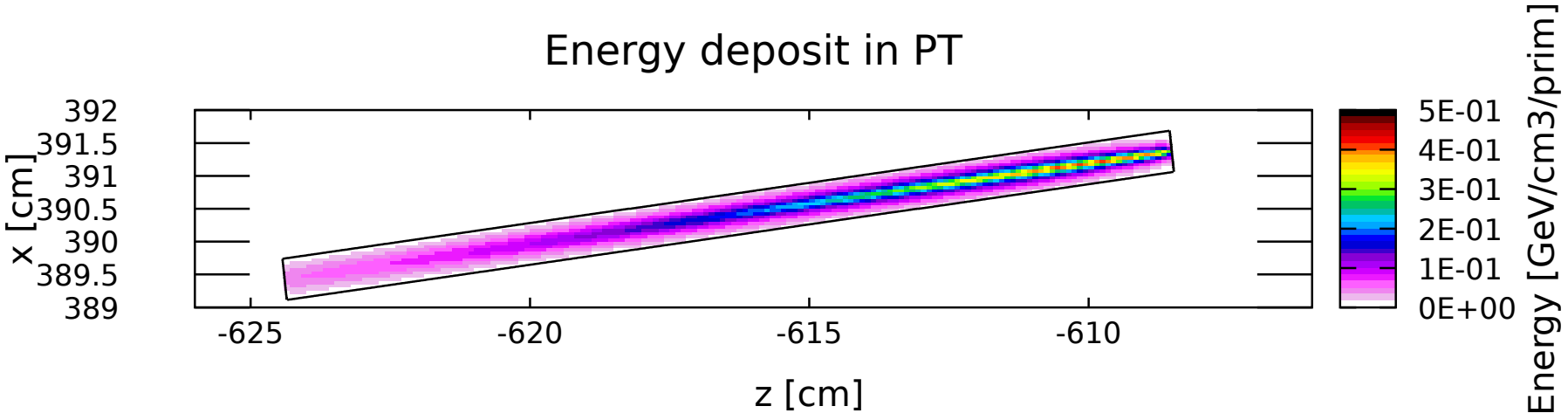

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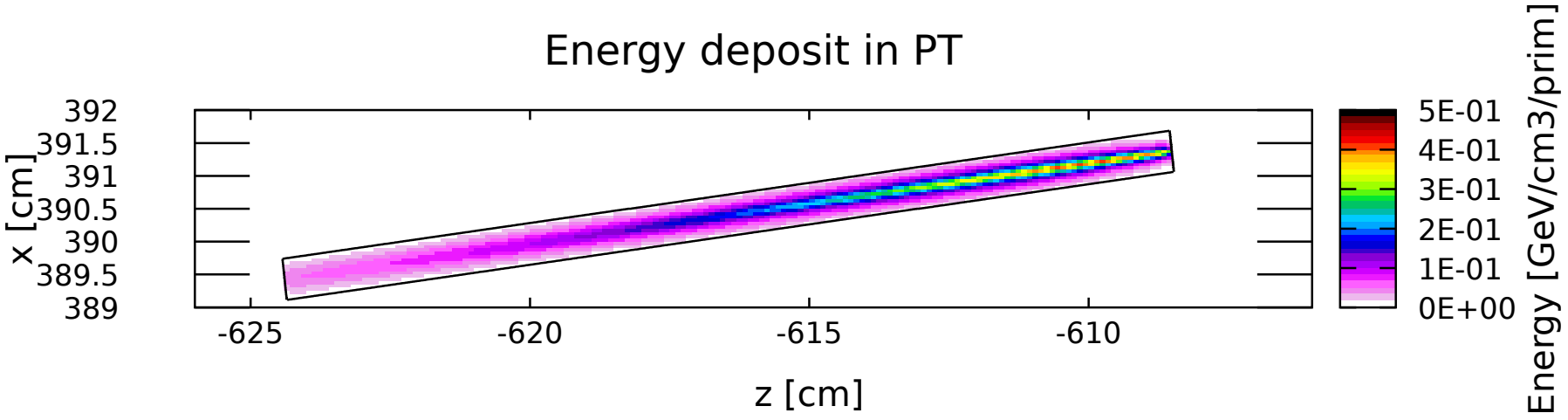

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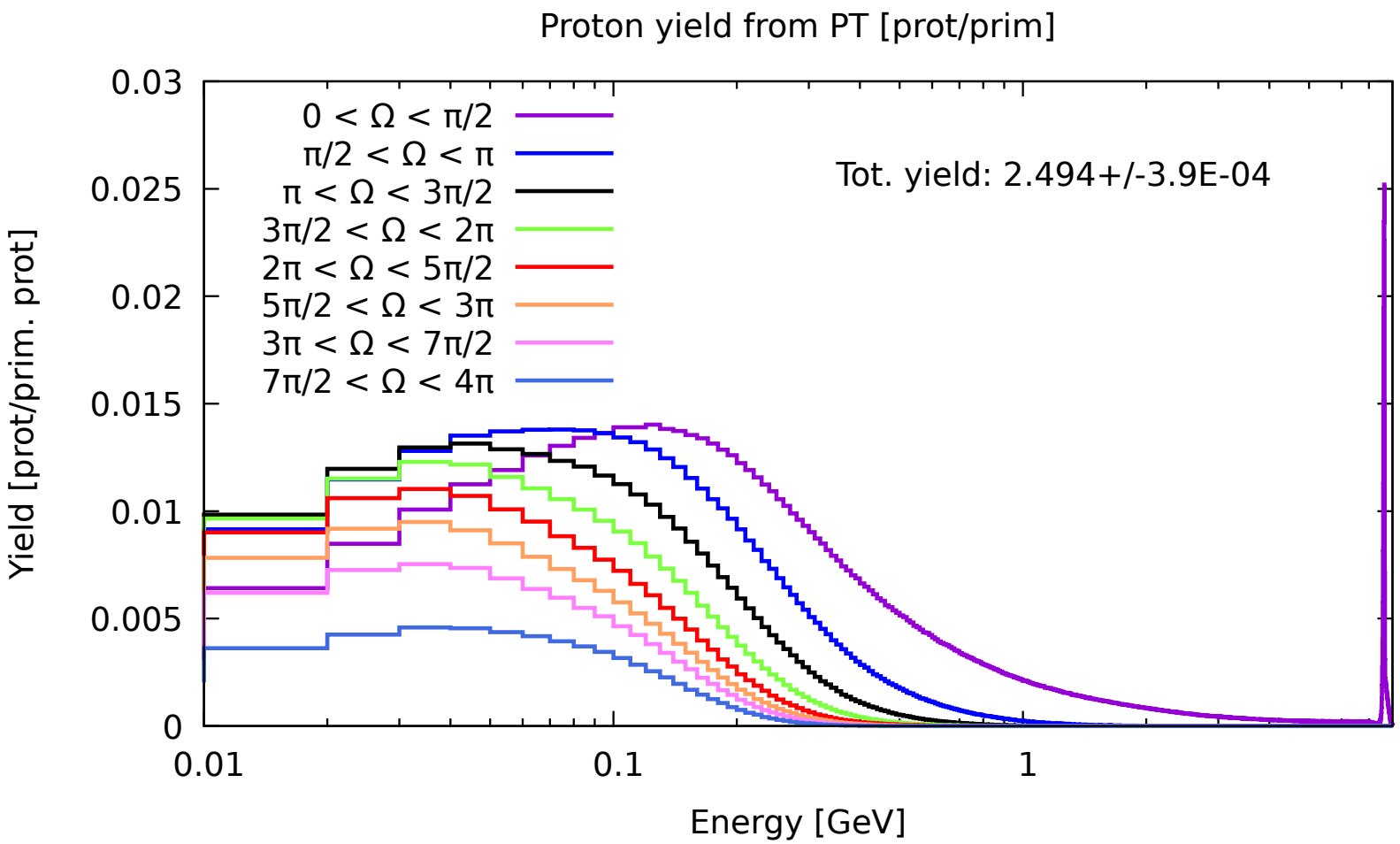
In good agreement with the results obtained with G4Beamline and MARS codes:

703 Watt@7.3kW beam power (G4Beamline)

713 Watt@7.3kW beam power (MARS)

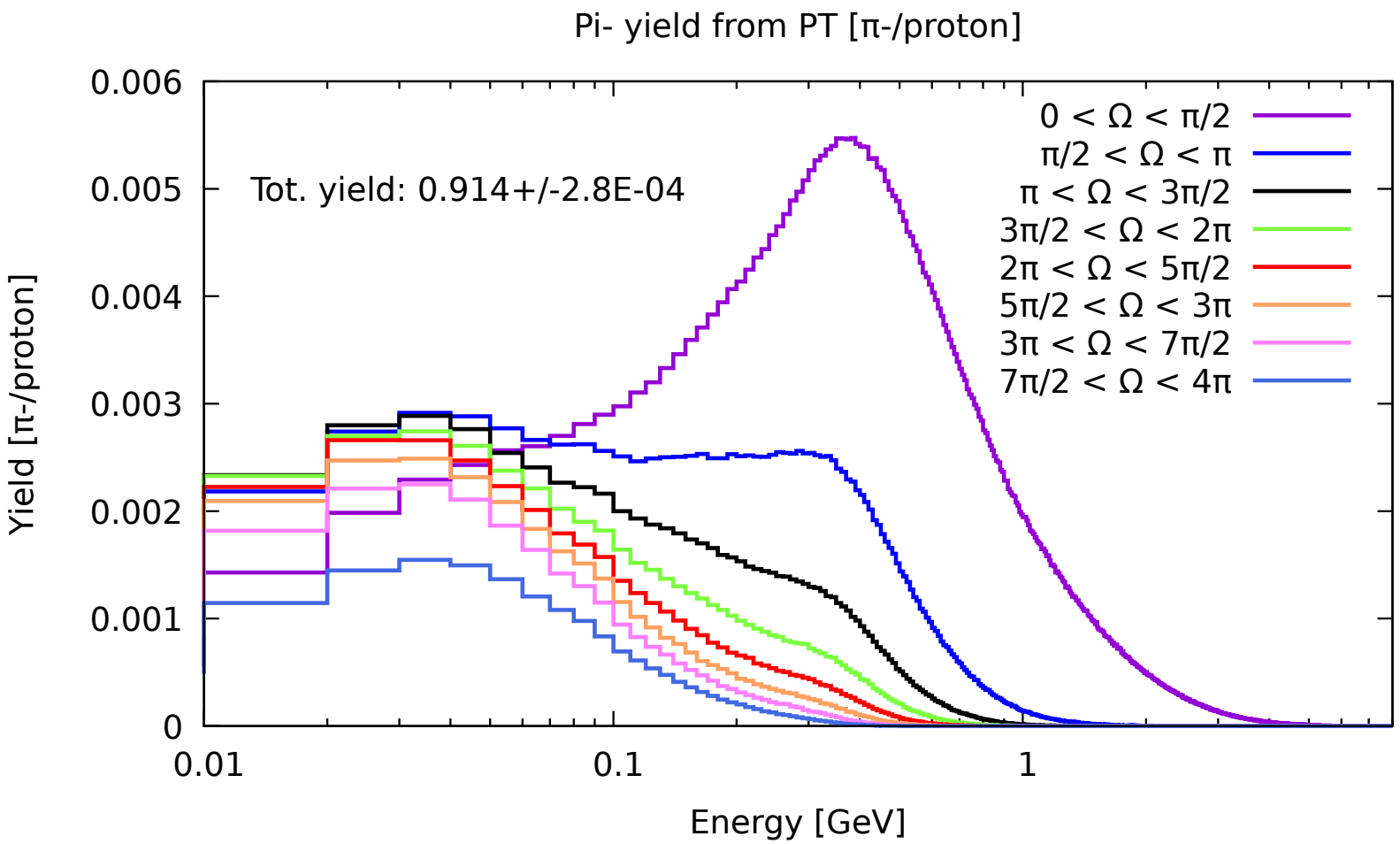
Proton yield emitted from production target

Yield of protons from production target in 8 bins of solid angle respect to initial proton beam direction:



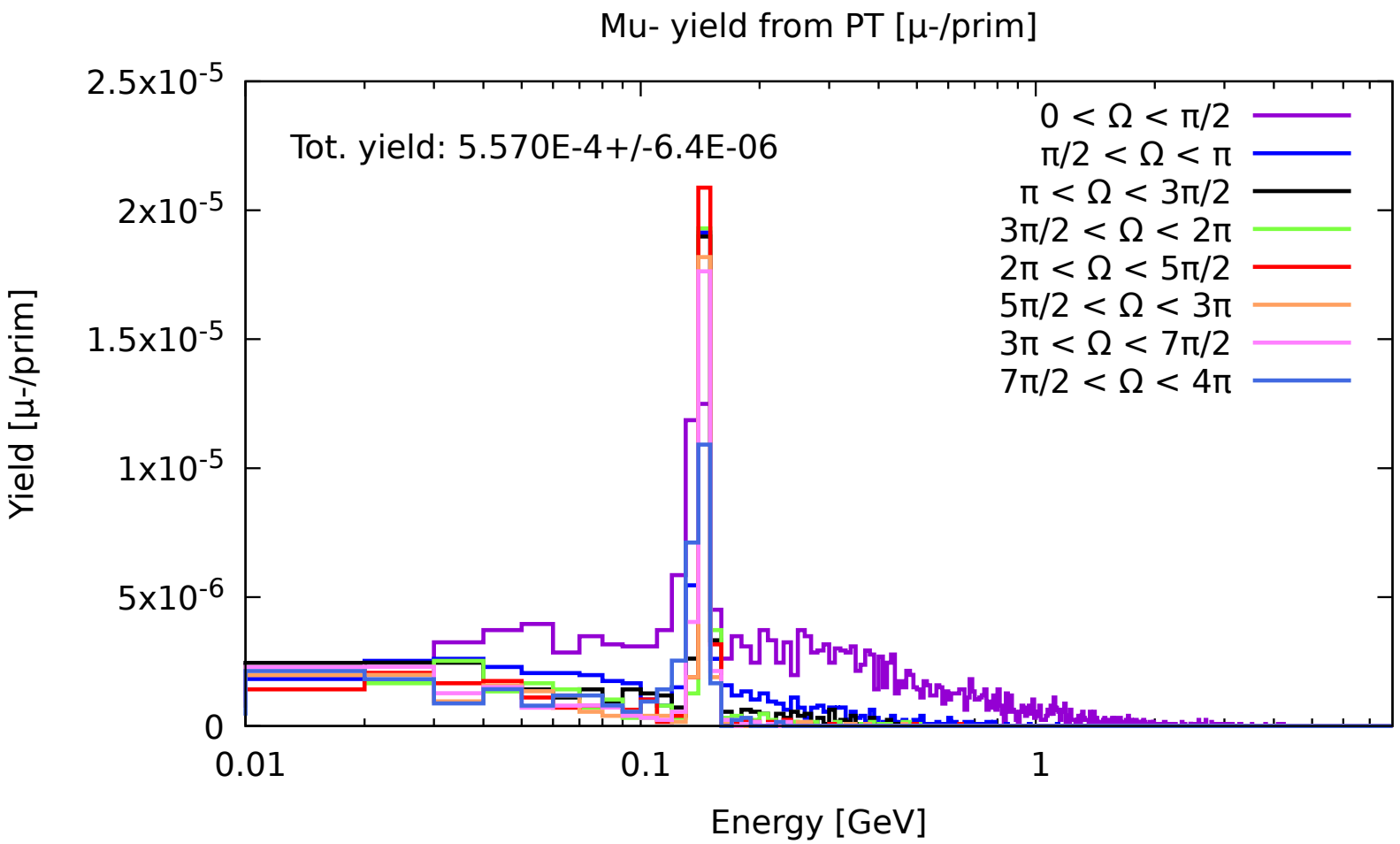
Pi- yield emitted from production target

Yield of negative pions from production target in 8 bins of solid angle respect to initial proton beam direction:



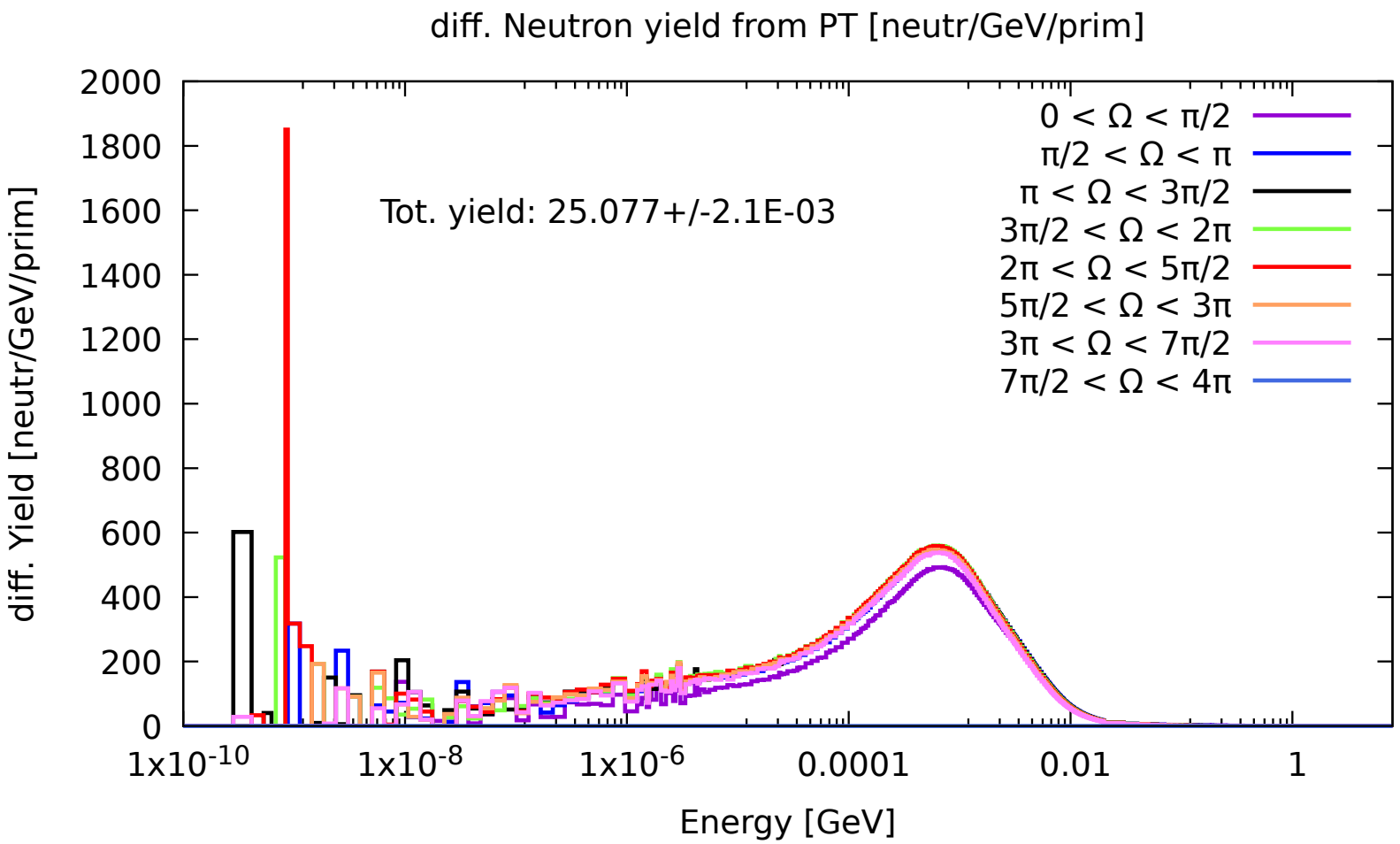
Mu- yield emitted from production target

Yield of negative muons from production target in 8 bins of solid angle respect to initial proton beam direction:



Diff. neutron yield emitted from production target

Diff. yield of neutrons from production target in 8 bins of solid angle respect to initial proton beam direction:



Geometry

Several ROOT "helper" macros had been developed to convert **GEANT4** solids and volumes to **FLUKA** bodies and regions

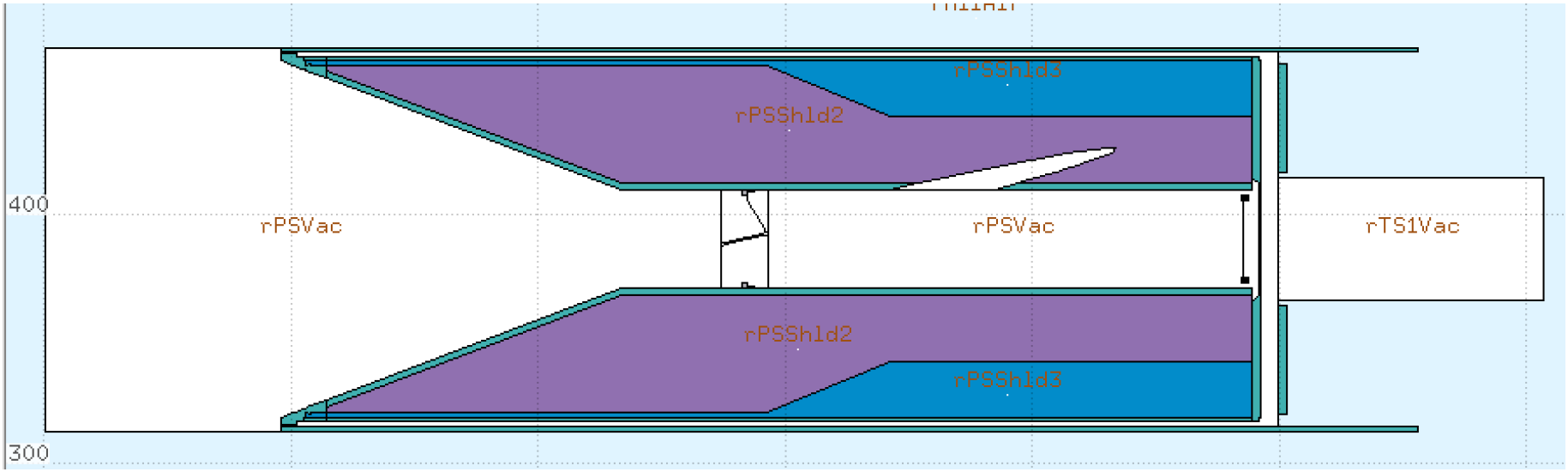
```
void buildTubs(string name, Double_t in[5],
       Double_t tr[3], Double_t trMV[3],
      TGeoRotation rot[3*3])

void buildBox(string name, Double_t in[3],
       Double_t tr[3], Double_t trMV[3],
      TGeoRotation rot[3*3])

void buildTRC(string name, Double_t in[6],
       Double_t tr[3], Double_t trMV[3],
      TGeoRotation rot[3*3])
```

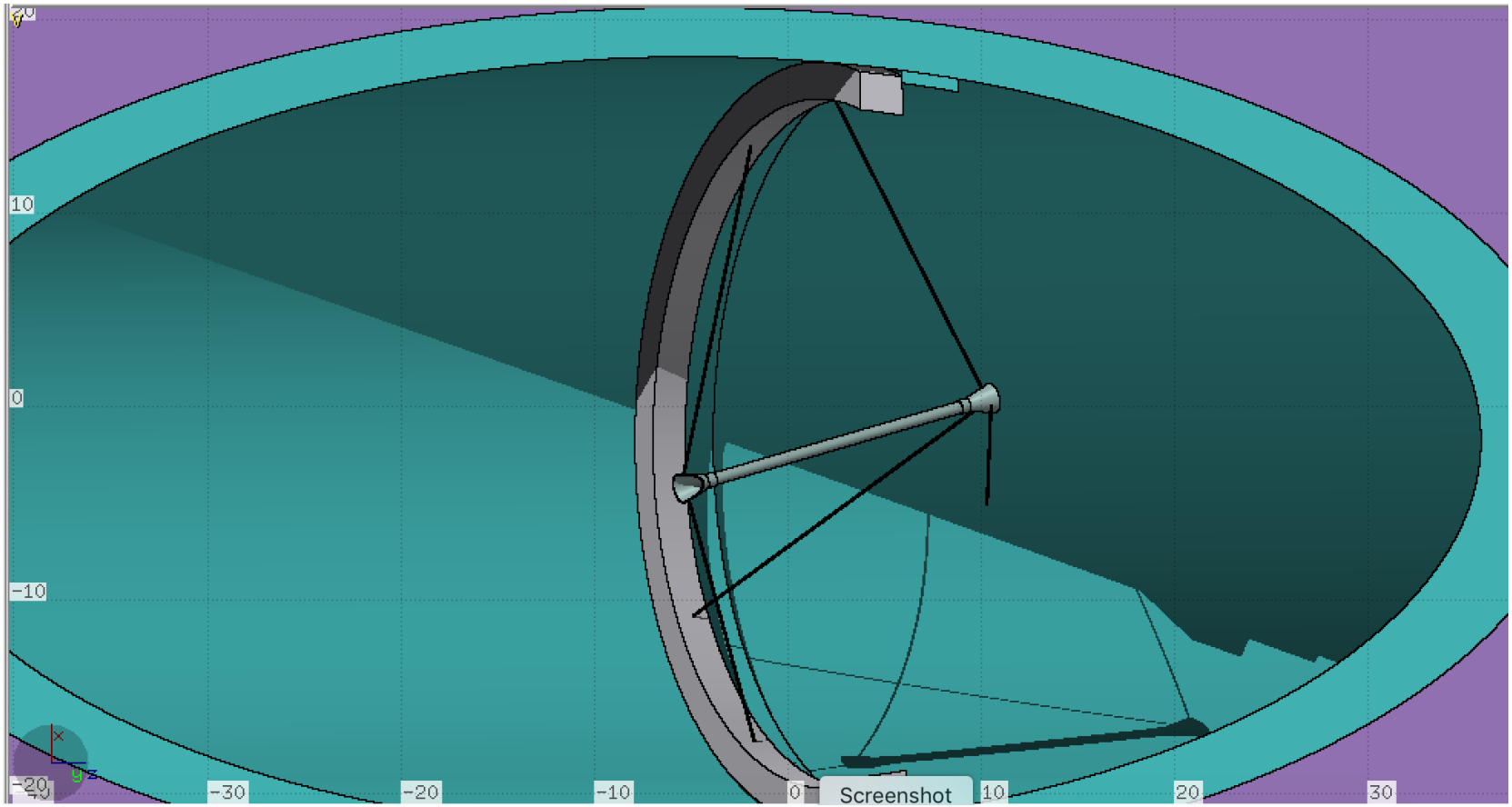
Geometry details summer 2019:

XZ-view of `PSVacuum`-Volume:



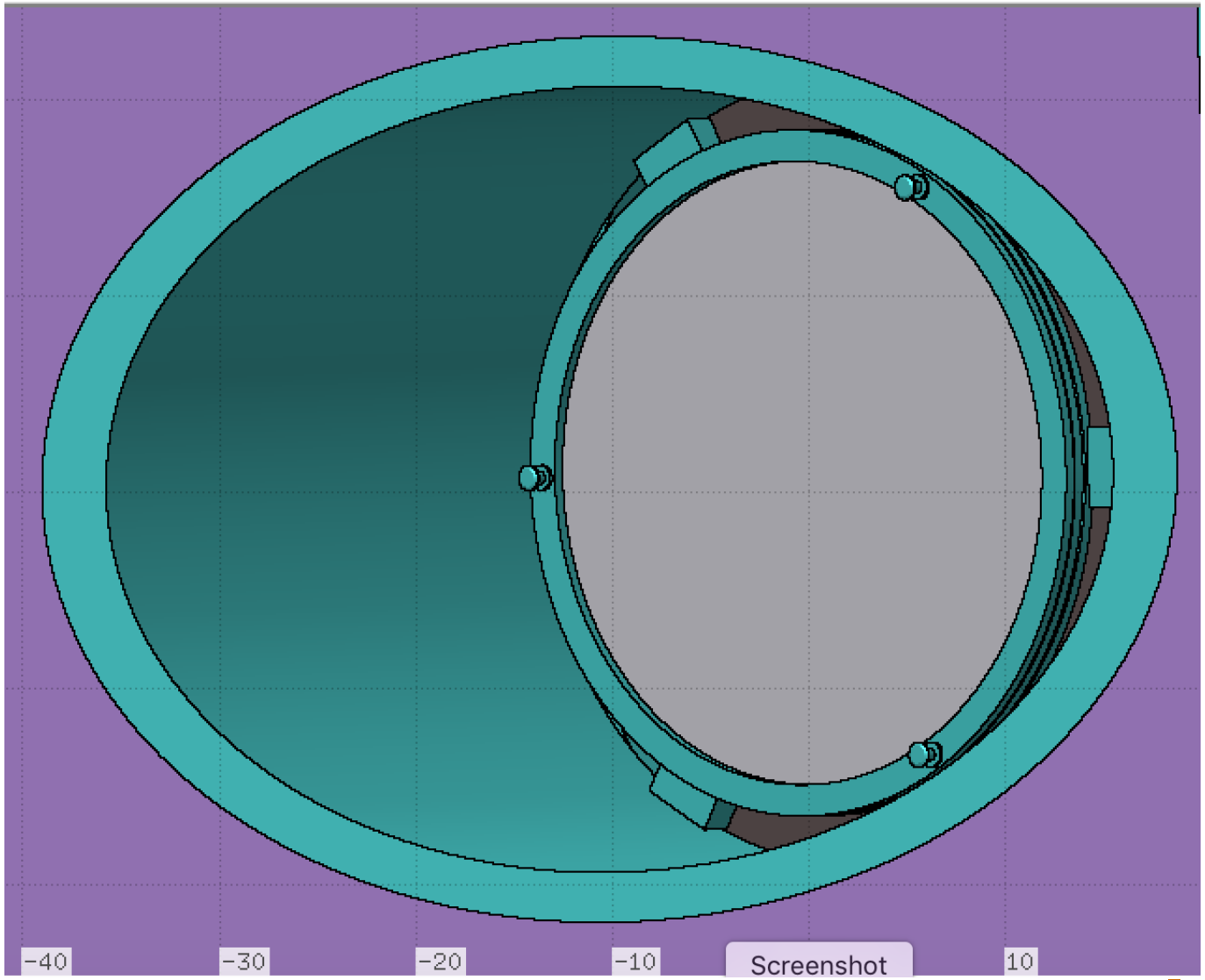
Geometry details summer 2019:

Production target:



Geometry details summer 2019:

Antiprotonabsorber:



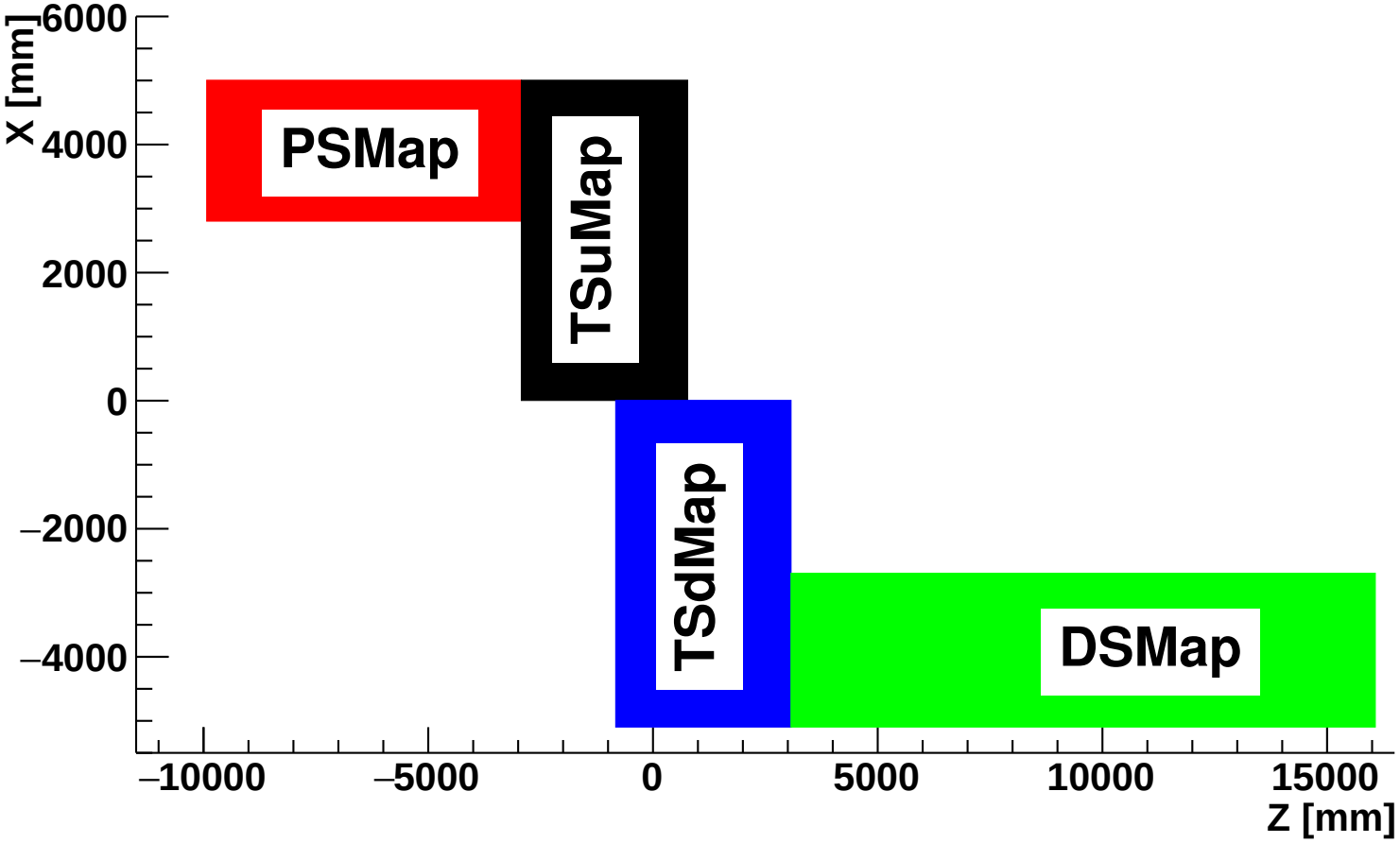
Magnetic fieldmaps at Mu2e

Inner fieldmaps of Mu2e grid structure:

PSMap	280 MByte	
	$2804 < x < 5004$mm	89 bins with $\Delta x = 25$mm
	$-1200 < y < 1200$mm	97 bins with $\Delta y = 25$mm
	$-9929 < z < -2929$mm	281 bins with $\Delta z = 25$mm
TSuMap	336 MByte	
	$4 < x < 5004$mm	201 bins with $\Delta x = 25$mm
	$-1200 < y < 1200$mm	97 bins with $\Delta y = 25$mm
	$-2929 < z < 771$mm	149 bins with $\Delta z = 25$mm
TSdMap	361 MByte	
	$-5096 < x < 4$mm	205 bins with $\Delta x = 25$mm
	$-1200 < y < 1200$mm	97 bins with $\Delta y = 25$mm
	$-829 < z < 3071$mm	157 bins with $\Delta z = 25$mm
DSMap	566 MByte	
	$-5096 < x < -2696$mm	97 bins with $\Delta x = 25$mm
	$-1200 < y < 1200$mm	97 bins with $\Delta y = 25$mm
	$3071 < z < 16071$mm	521 bins with $\Delta z = 25$mm

Magnetic fieldmaps at Mu2e

Inner fieldmaps of Mu2e:

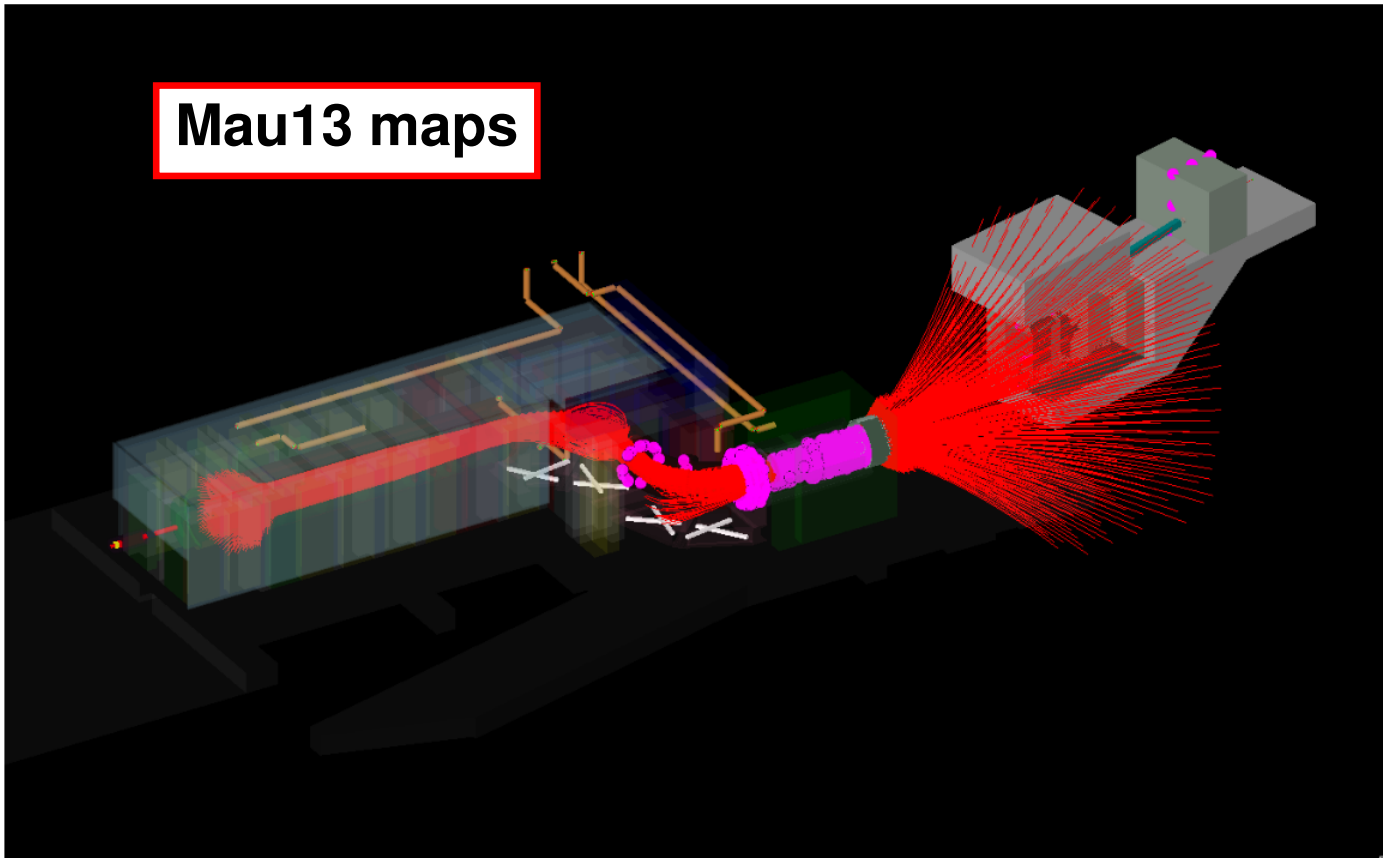


Displaying fieldmaps with G4Beamline

Mu2e magnetic fieldlines displayed with **G4Beamline** v3.06 adding

```
fieldlines exit=0 center=0,0,0 nLines=500 radius=900 color=1,0,0
```

to the input file, and executing `g4bl Mu2E.in viewer=best`



Mu2e fieldmaps in FLUKA

Custom definition of magnetic field is possible via external fortran routines which are linked to the standard FLUKA executable.

Fieldmaps are read in at begin of each run via customized `usrini.f` external routine.

The routine `magfield_MU2E.f` is called during the transport calculation in **FLUKA** and calls the routine `fldval.f` which performs a trilinear interpolation from the grid points to the current point of interest (`https://en.wikipedia.org/wiki/Trilinear_interpolation#Method`).

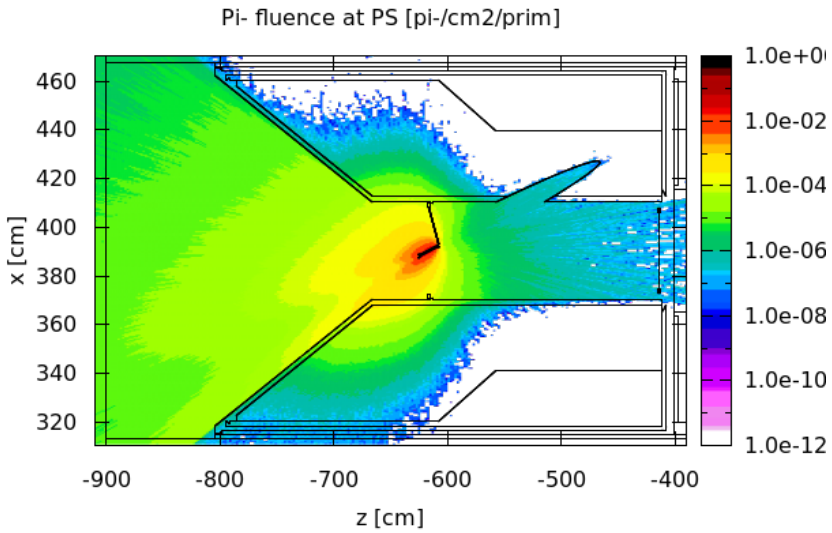
Succesfully imported the Mu2e maps into FLUKA

Simulations with and without magnetic field

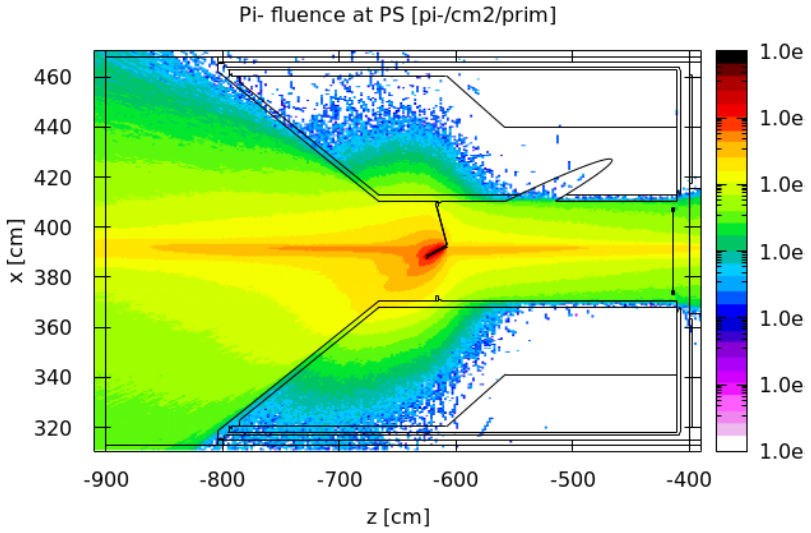
- **FLUKA** `2011.2x.6` version used
- 25 Mio. events for simulation without magnetic field
- 11 Mio. events for simulation with magnetic field
- Source term: Proton beam hitting production target
  - 8 GeV kin. energy
  - Gaussian smearing of position with 1mm sigma
- Scoring:
  - 2d-plots of particle fluence in `XZ`-plane
  - Diff. Particle yield entering TS1 (corresponding to VD Coll1_In), incl. in angle, 10 MeV binwidth in energy

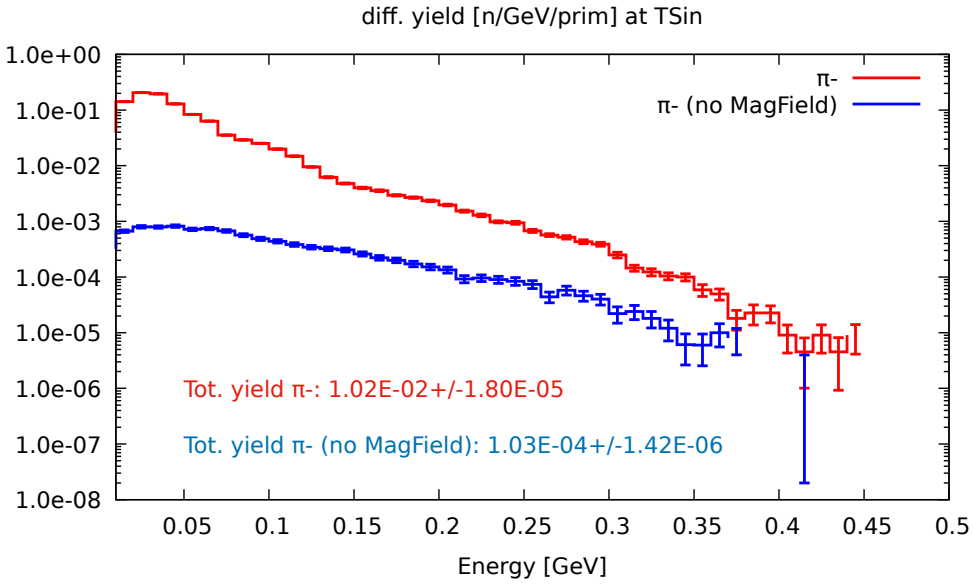
Fluence results for π^- in the PS:

Magnetic field OFF:



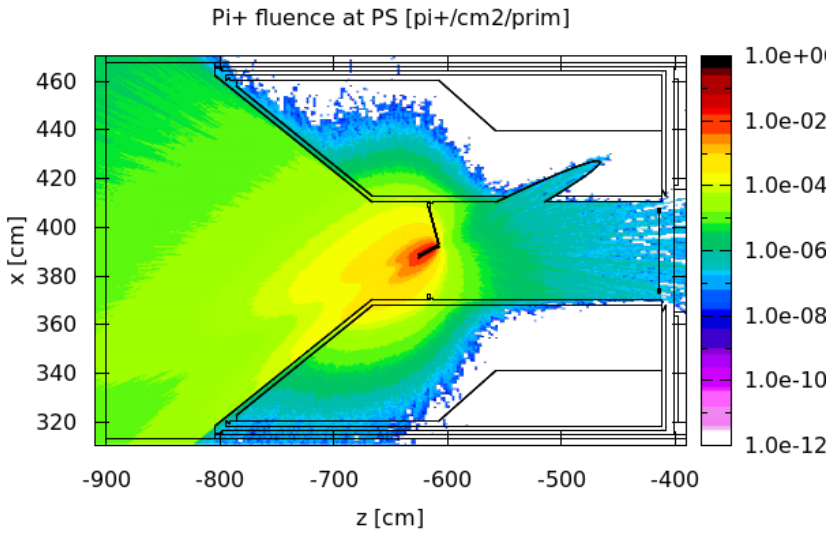
Magnetic field ON:



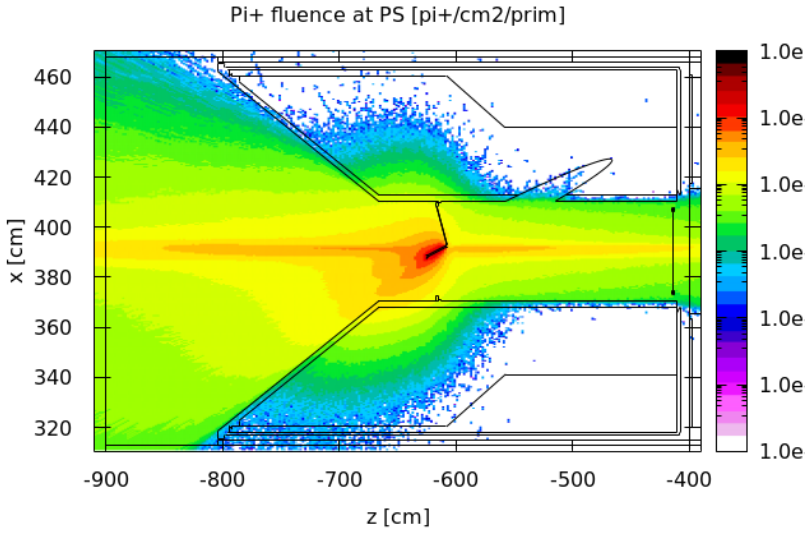


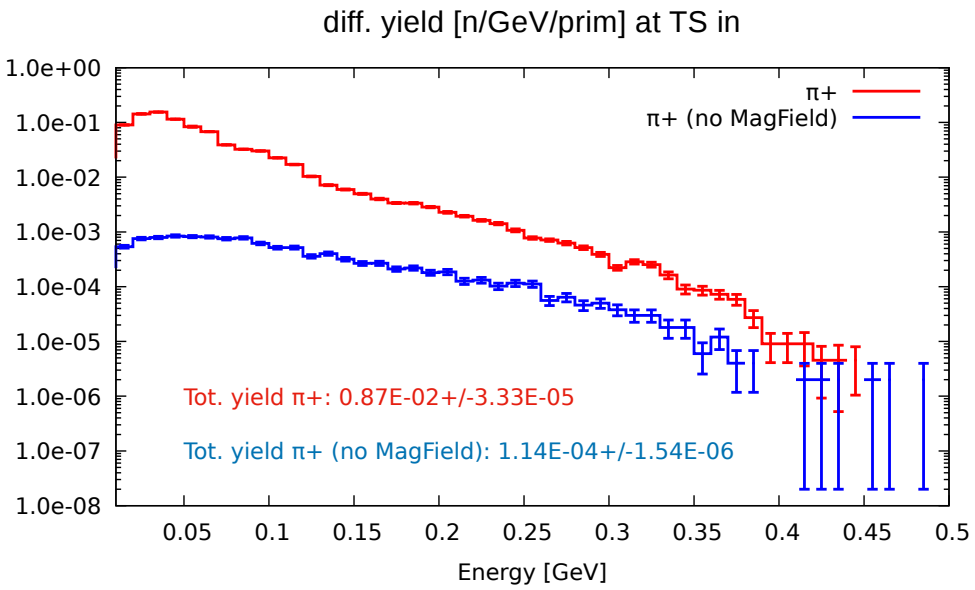
Fluence results for π^+ in the PS:

Magnetic field OFF:



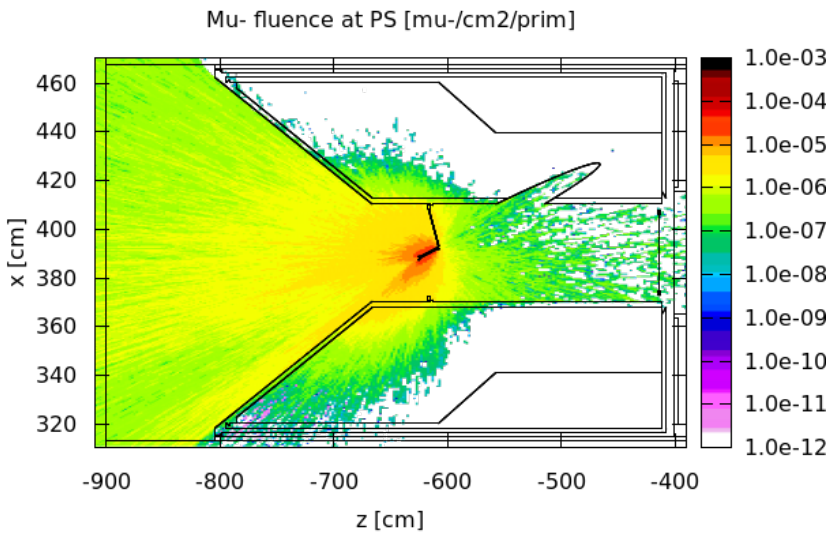
Magnetic field ON:



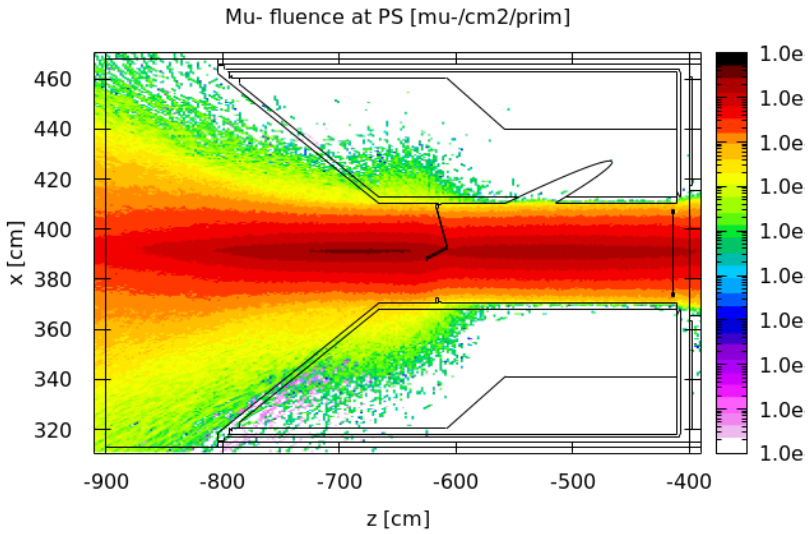


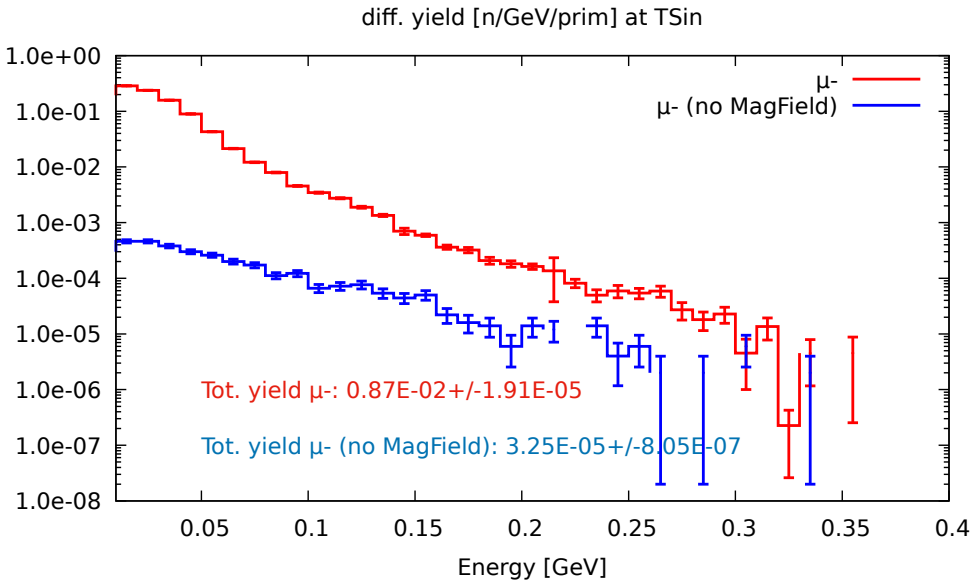
Fluence results for μ^- in the PS:

Magnetic field OFF:



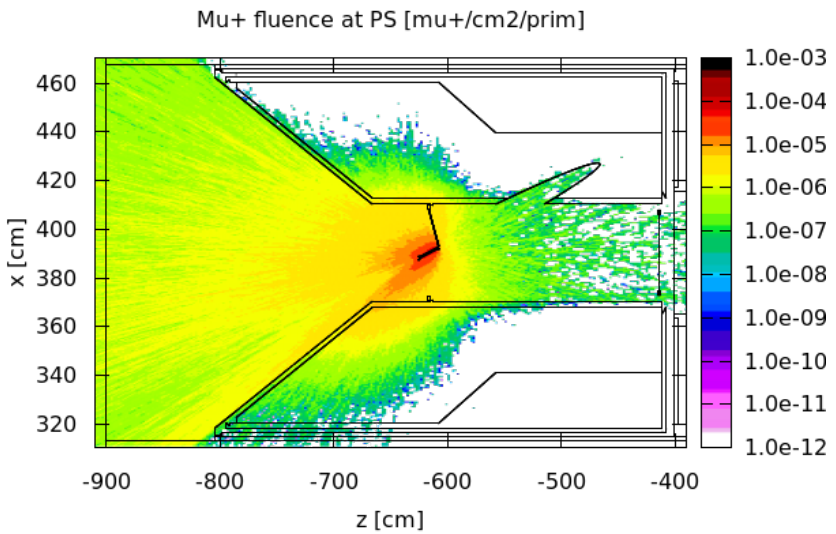
Magnetic field ON:



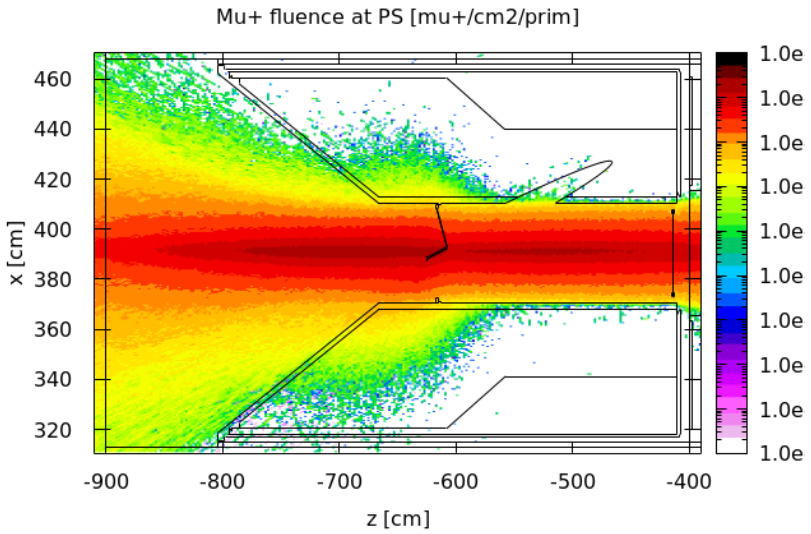


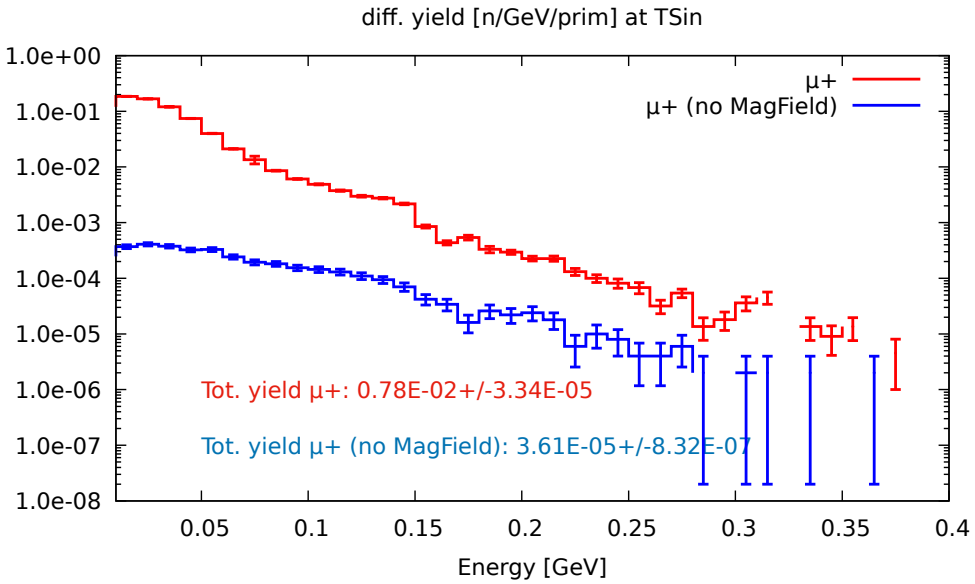
Fluence results for μ^+ in the PS:

Magnetic field OFF:



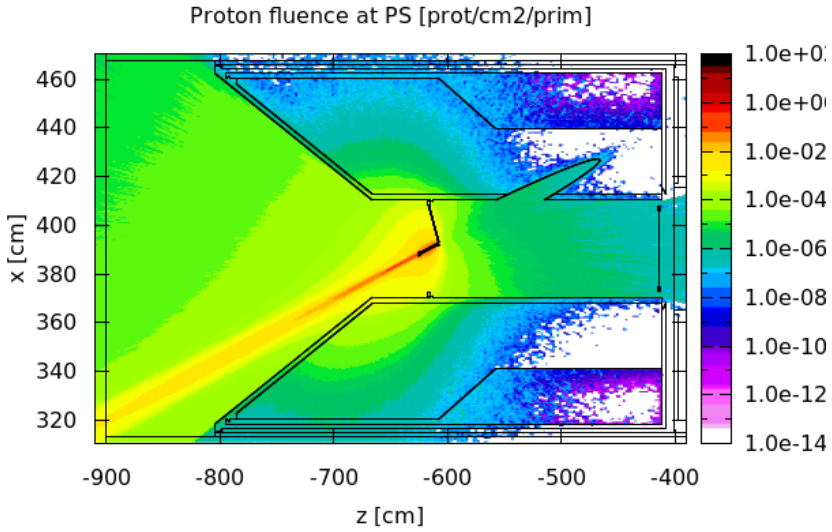
Magnetic field ON:



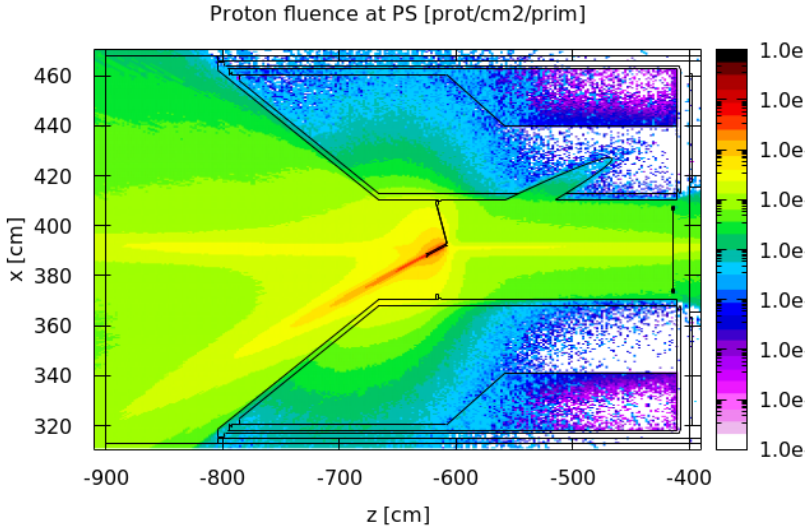


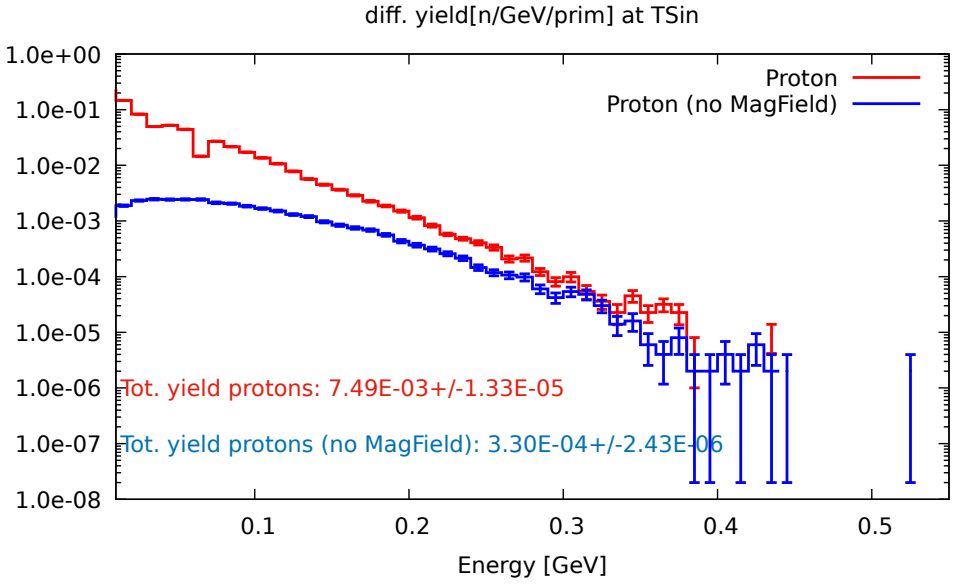
Fluence results for protons in the PS:

Magnetic field OFF:



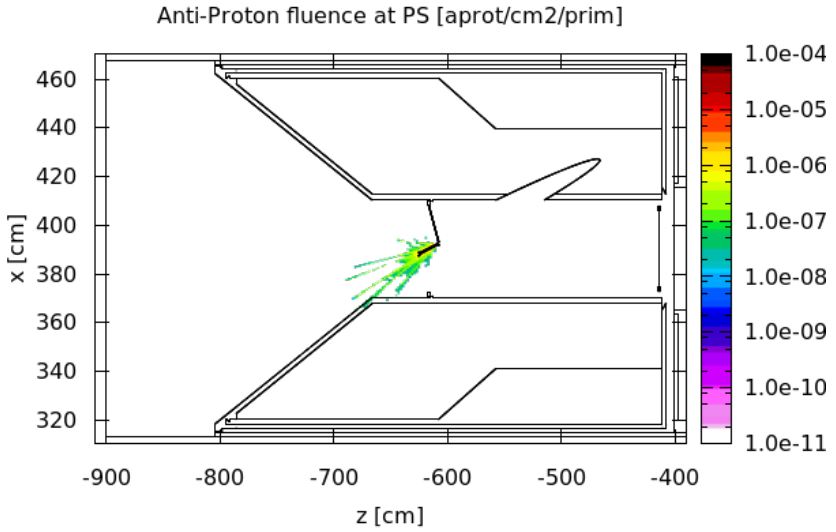
Magnetic field ON:



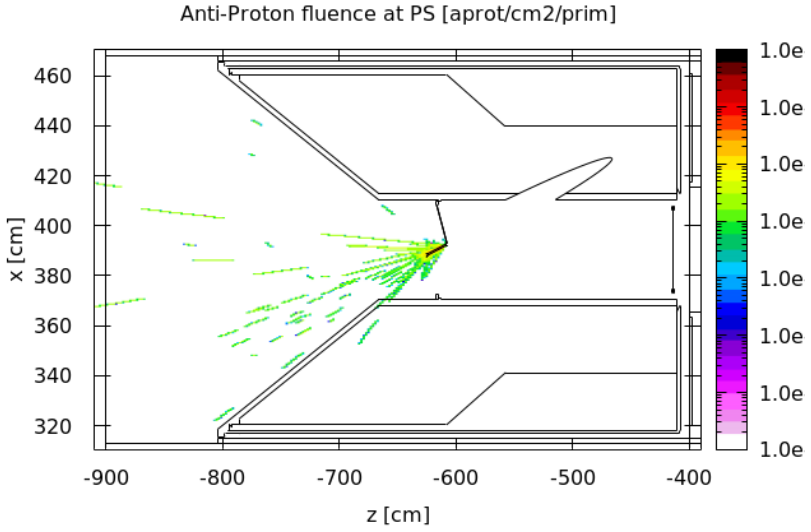


Fluence results for anti-protons in the PS:

Magnetic field OFF:



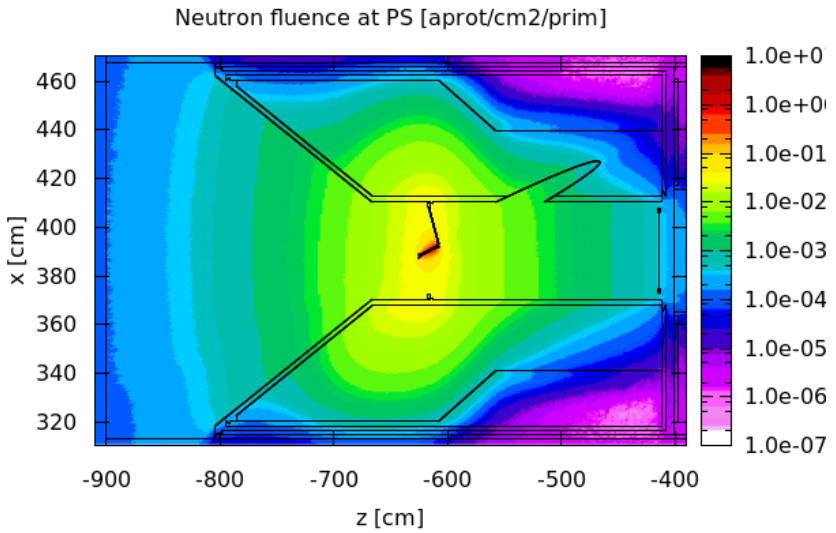
Magnetic field ON:



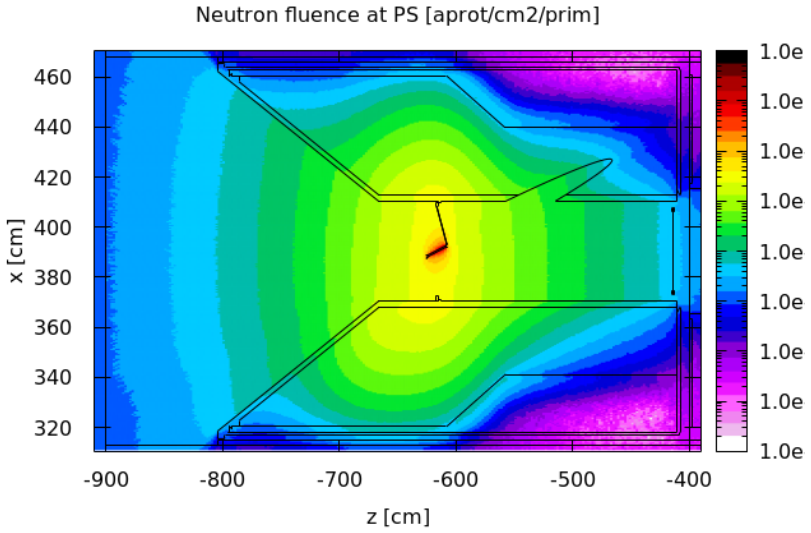
With the given statistics, no antiprotons make it to the TS!

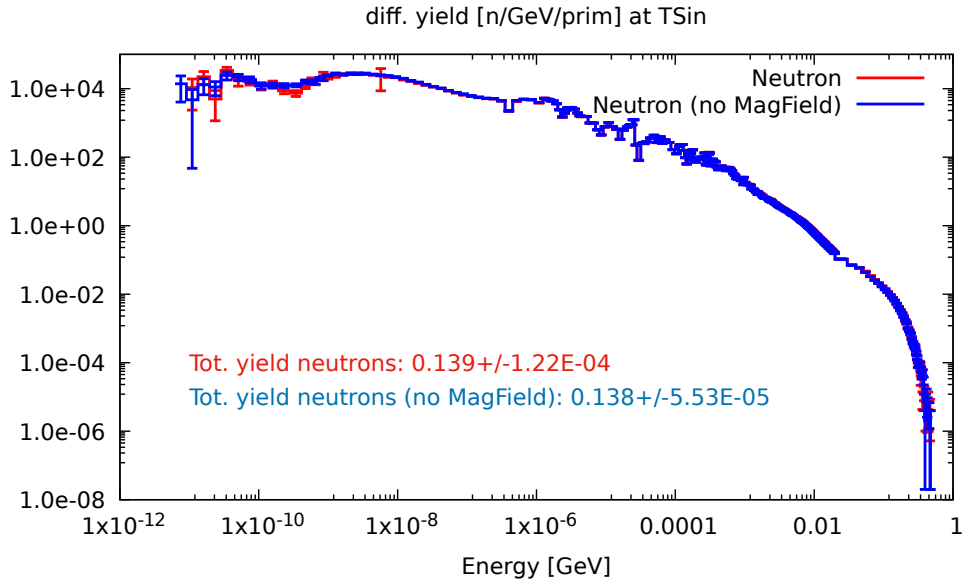
Fluence results for neutrons in the PS:

Magnetic field OFF:

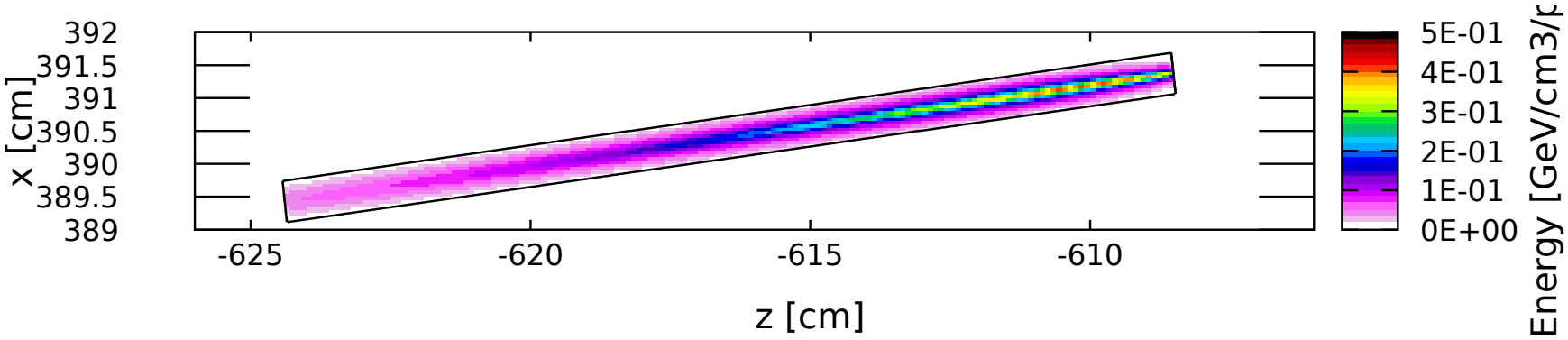


Magnetic field ON:





Energy deposition in target



Magnetic field OFF:

average energy deposition of
0.834 GeV/proton $\pm$ 0.01%,
which corresponds to
731 Watt@7.3kW beam power.

Magnetic field ON:

average energy deposition of
0.856 GeV/proton $\pm$ 0.02%,
which corresponds to
750 Watt@7.3kW beam power.

To be compared with

703 Watt@7.3kW beam power (G4Beamline)

713 Watt@7.3kW beam power (MARS)

Geometry

New `ROOT` "helper"macros for `G4Torus` and `G4ExtrudedSolid`:

```
void buildTorus(std::string name, Double_t in[6],
       Double_t tr[3], Double_t trMV[3],
      TGeoRotation rot[3*3])
```

`name` : 5 character name
`in[6]` : 6 parameters r_{min}, r_{max}, R, Φ_{min}, $\Delta\Phi$, n
`tr[3]` : translation vector of volume
`trMV[3]` : translation vector of mother volume
`rot[3*3]` : rotation matrix from `volumeDetails.txt`

Gives as output the contents of the body, region and rotation-matrix input cards to create a torus made of n cylindrical segments in **FLUKA**

Geometry

New ROOT "helper"macros for G4Torus and G4ExtrudedSolid:

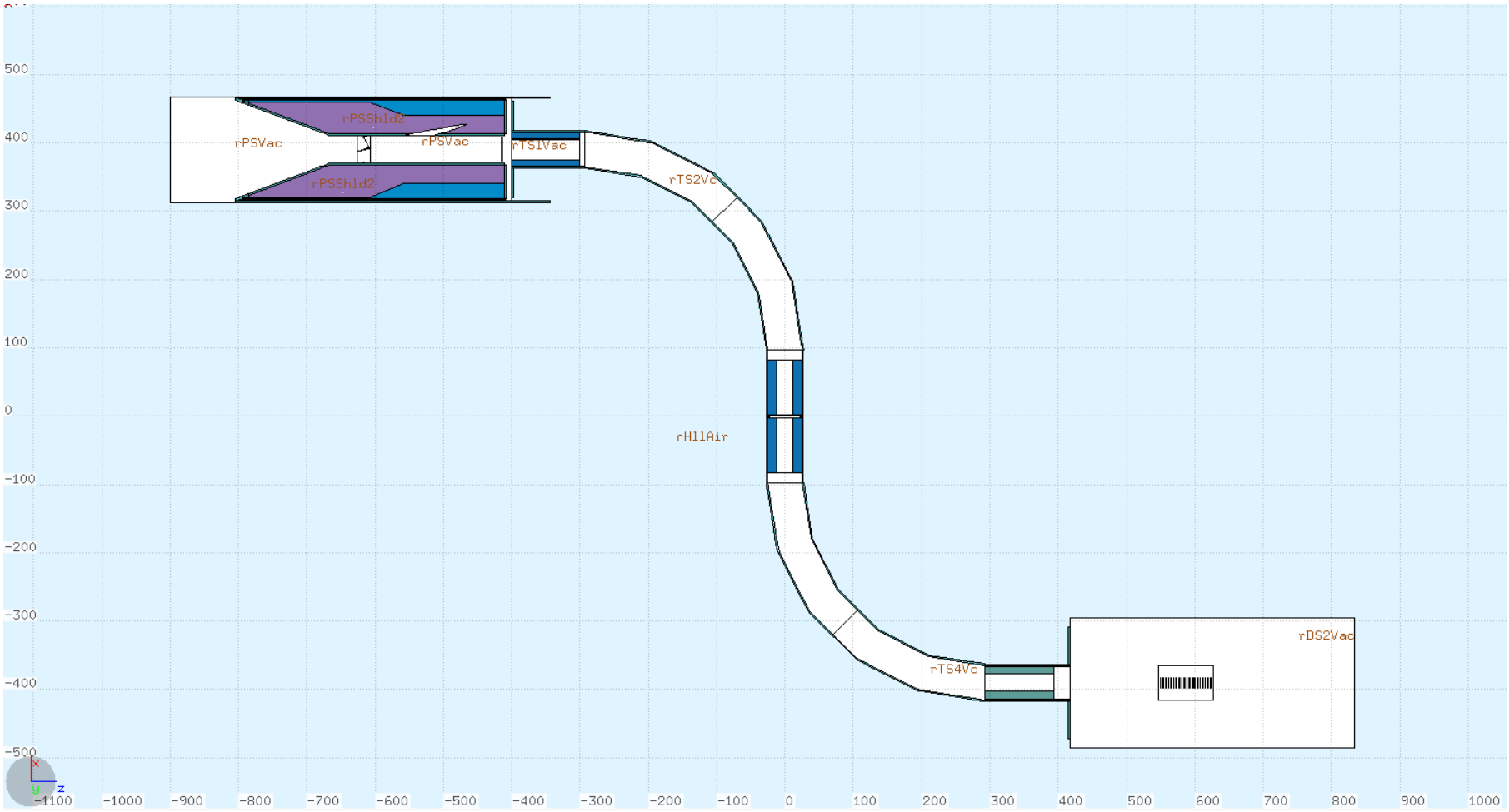
```
void buildExtrSolid(std::string name, vector <Double_t> x,
     vector <Double_t> y, vector <Double_t> z,
     Double_t tr[3], Double_t trMV[3],
     TGeoRotation rot[3*3])
```

name : 5 character name
x, y : vectors with (x,y) coordinates of base surface
z: vector with z-coordinates of planes
tr[3] : translation vector of volume
trMV[3] : translation vector of mother volume
rot[3*3] : rotation matrix from volumeDetails.txt

Gives as output the contents of the body, region and rotation-matrix input cards to create an Extruded Solid in **FLUKA**

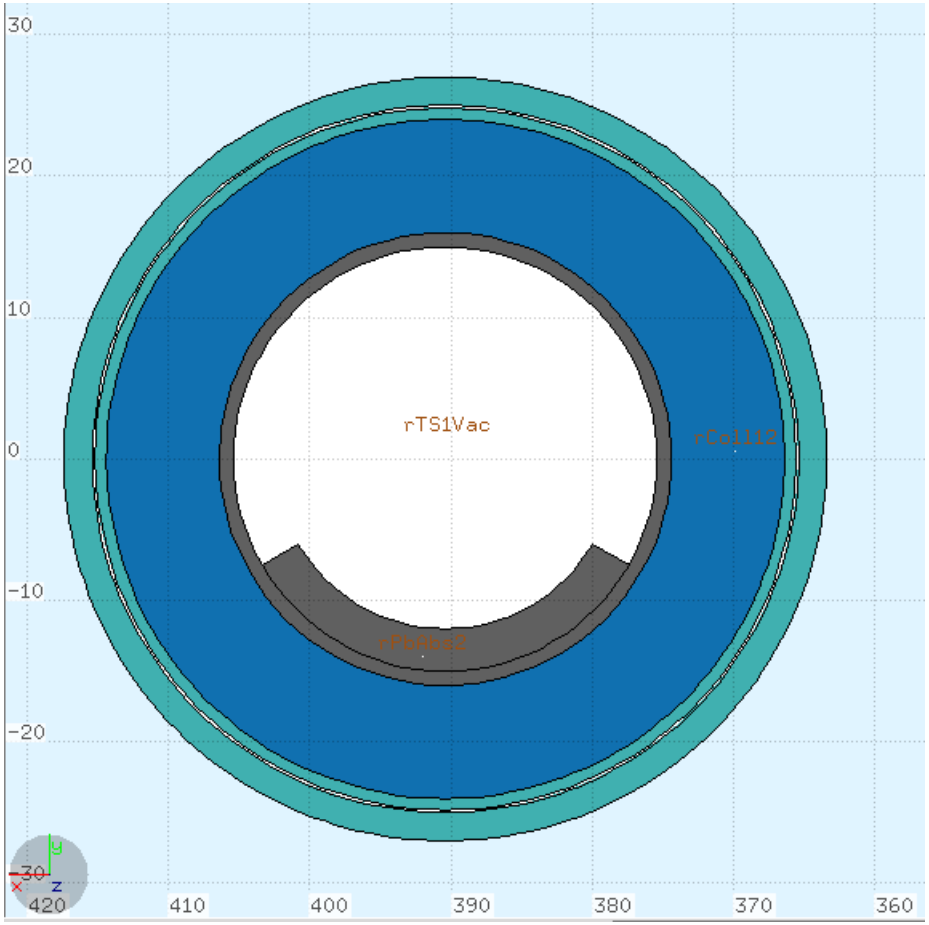
New FLUKA geometry with TS

TS2 and TS4 modeled with 5 segments each:



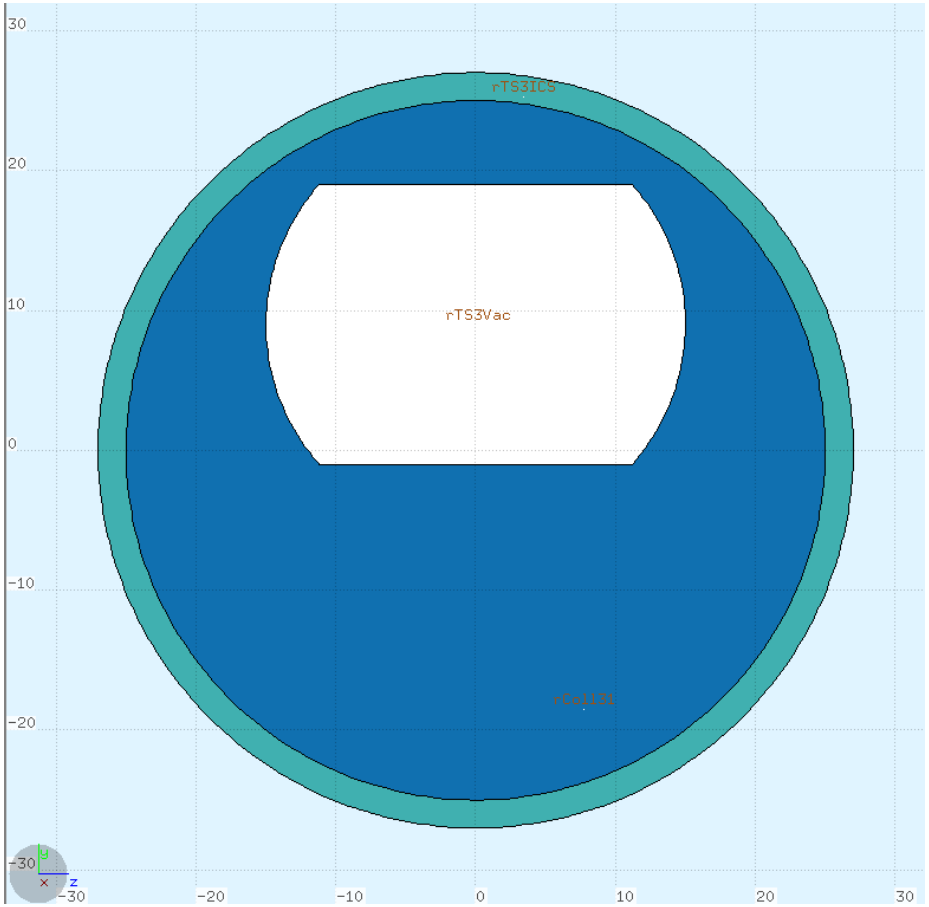
New FLUKA geometry with TS

TS1 with “collar” collimator:



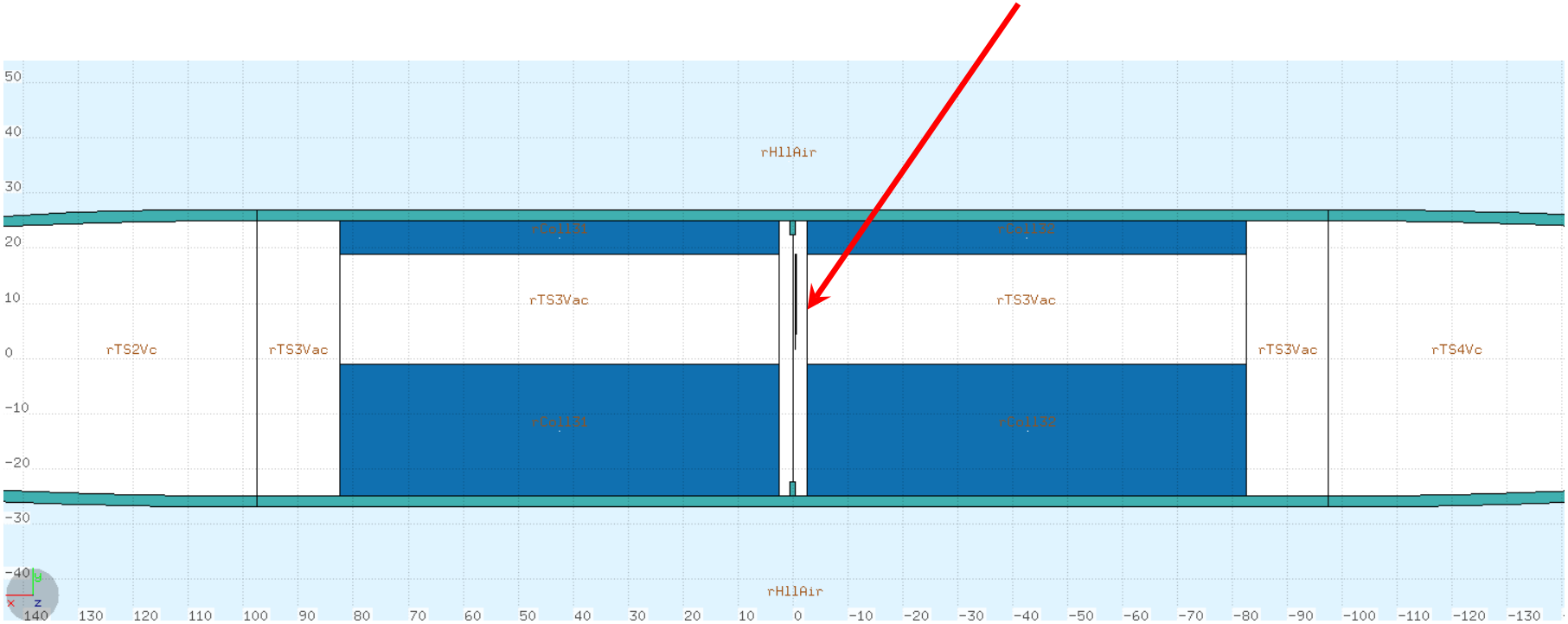
New FLUKA geometry with TS

TS3 aperture:



New FLUKA geometry with TS

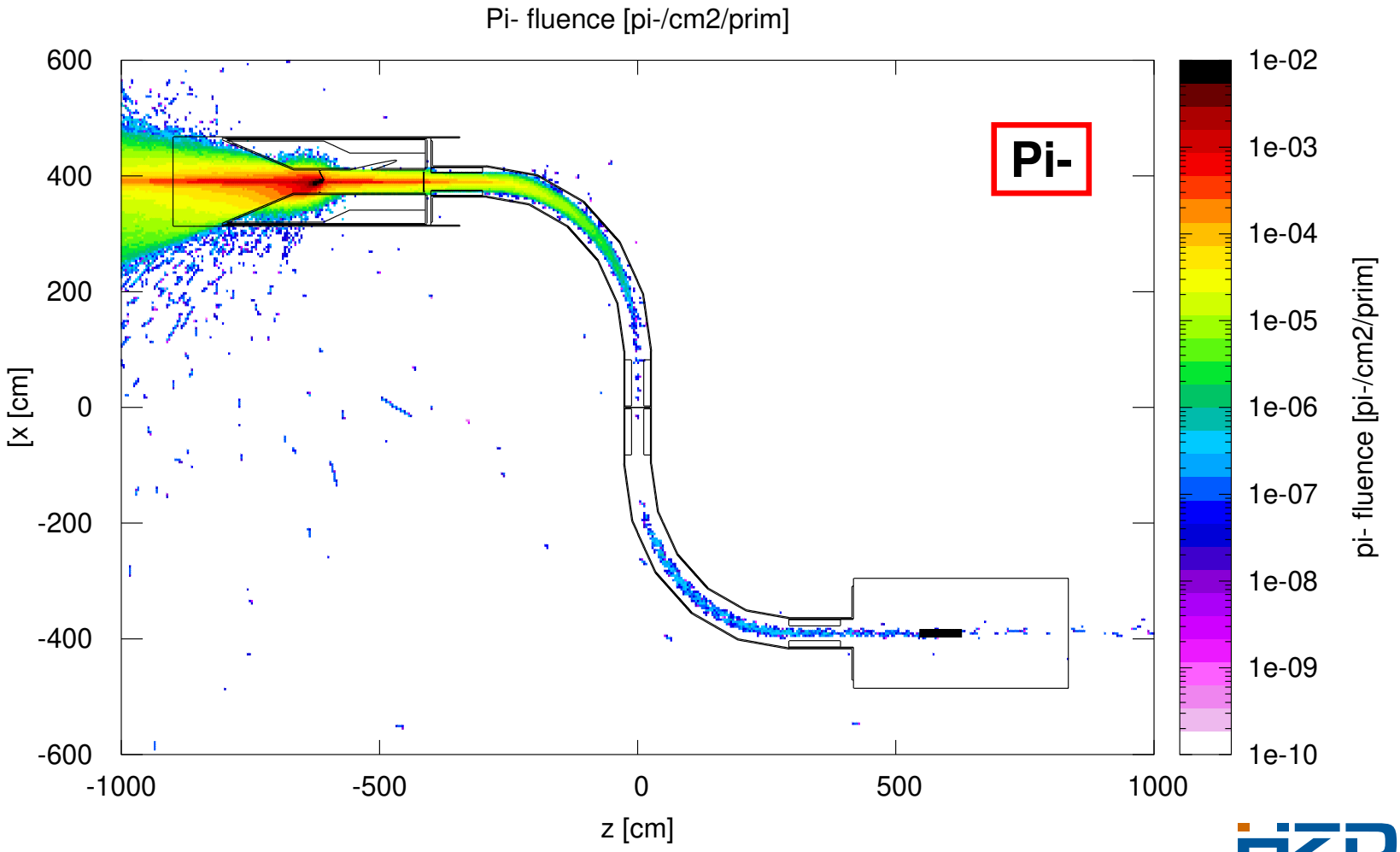
TS3 with aperture and extra absorber foils (extruded solid):



First results:

Results from a first production campaign

- 8 GeV protons on PT
- 1.7 Mio. events



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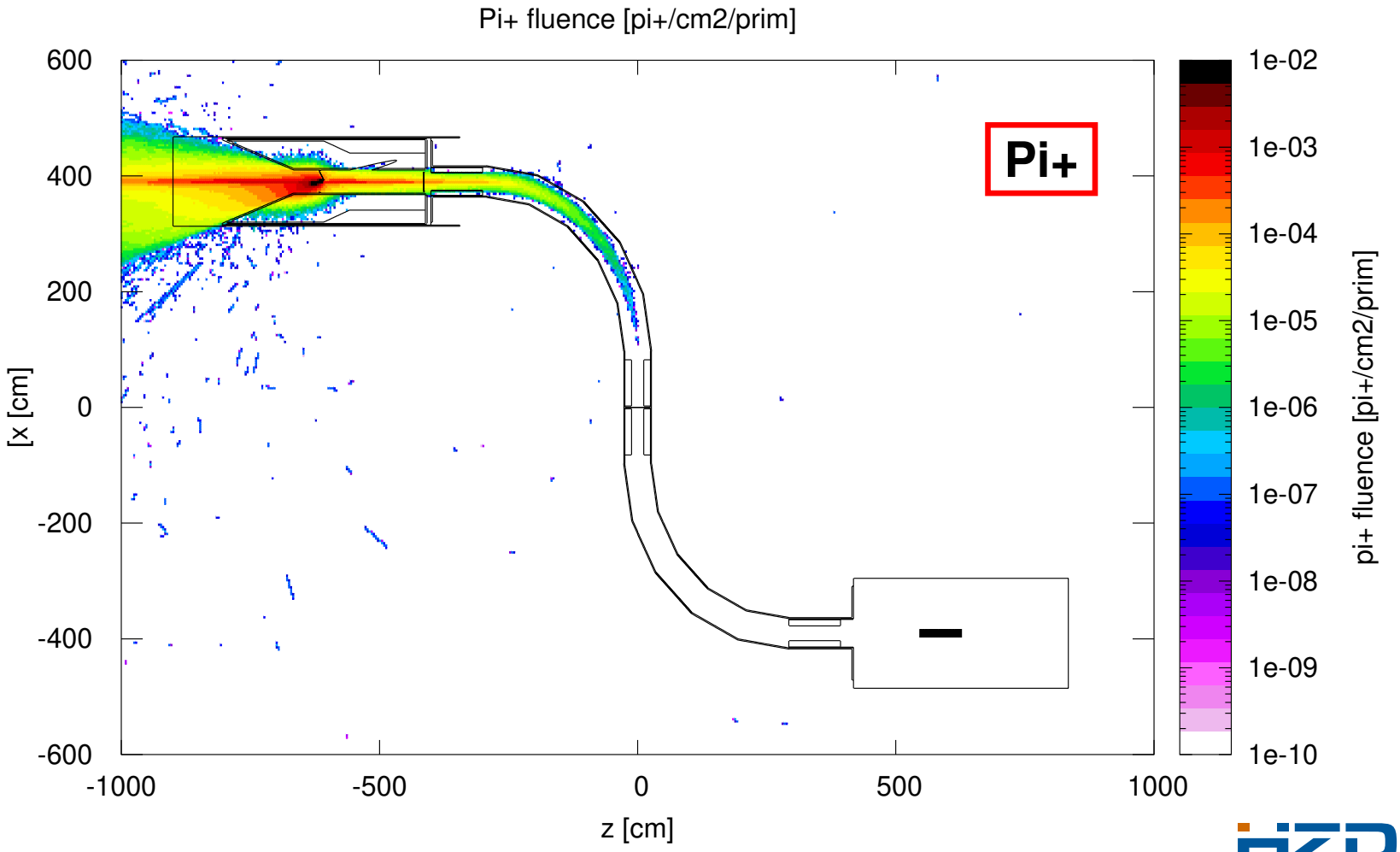

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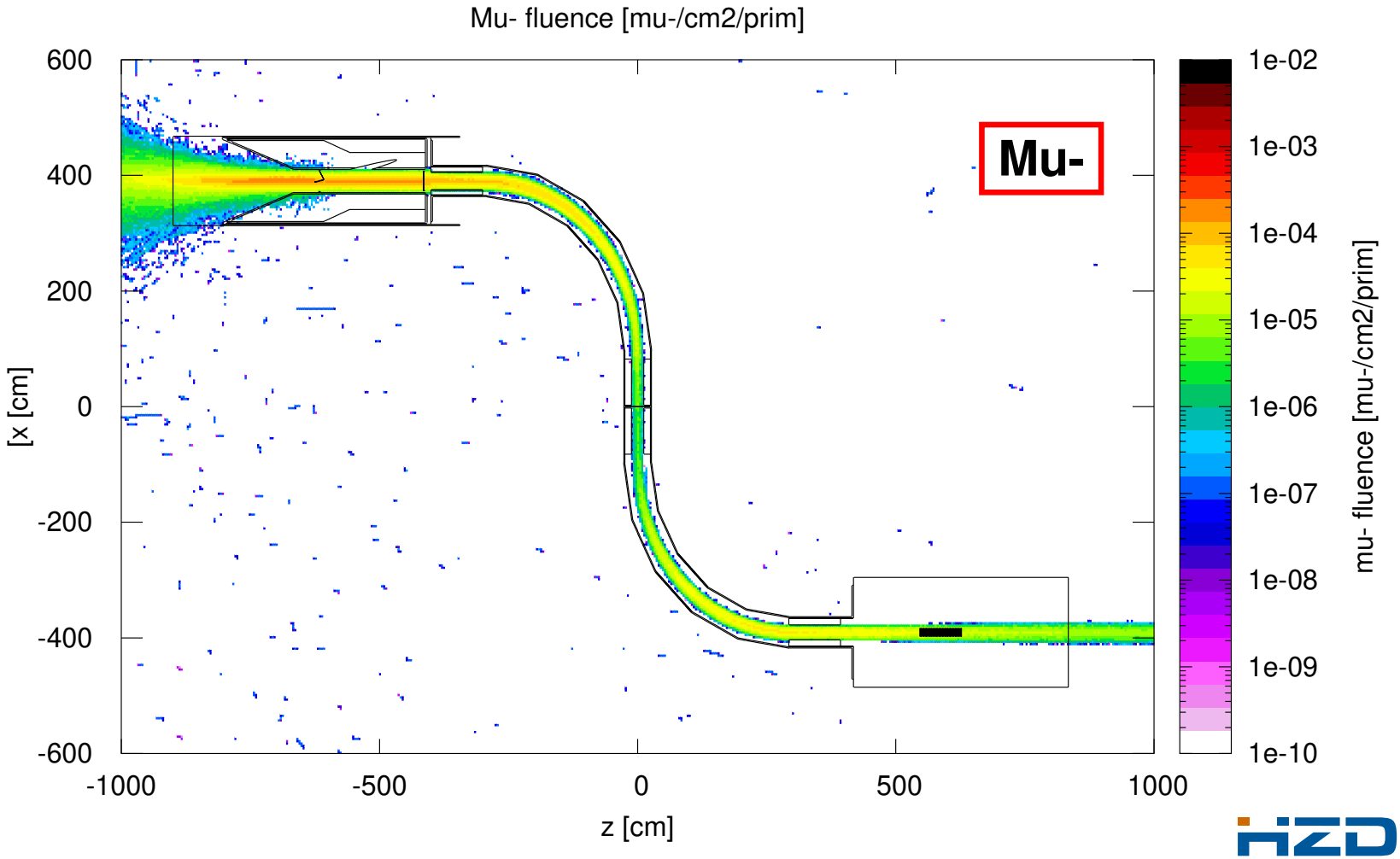

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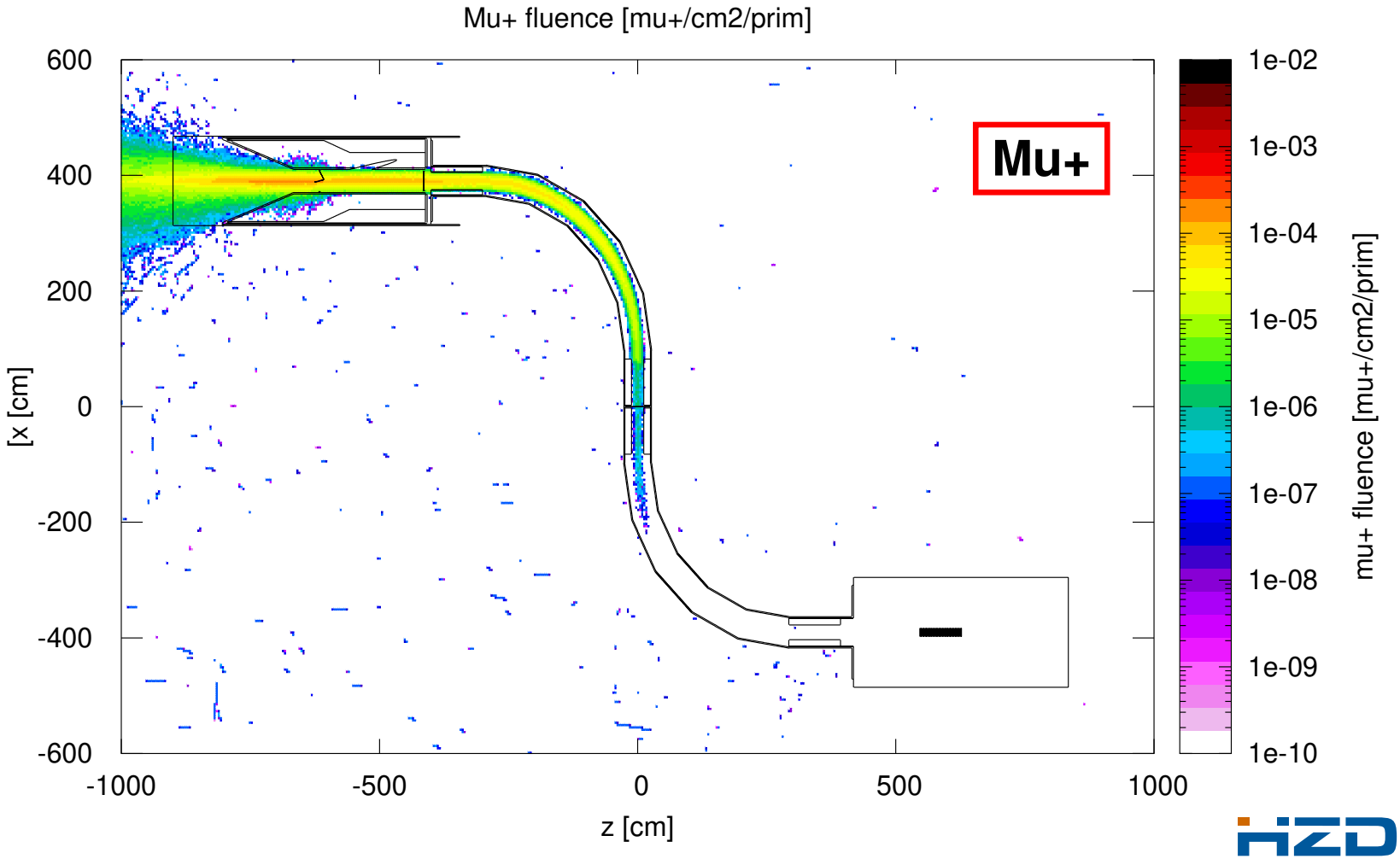

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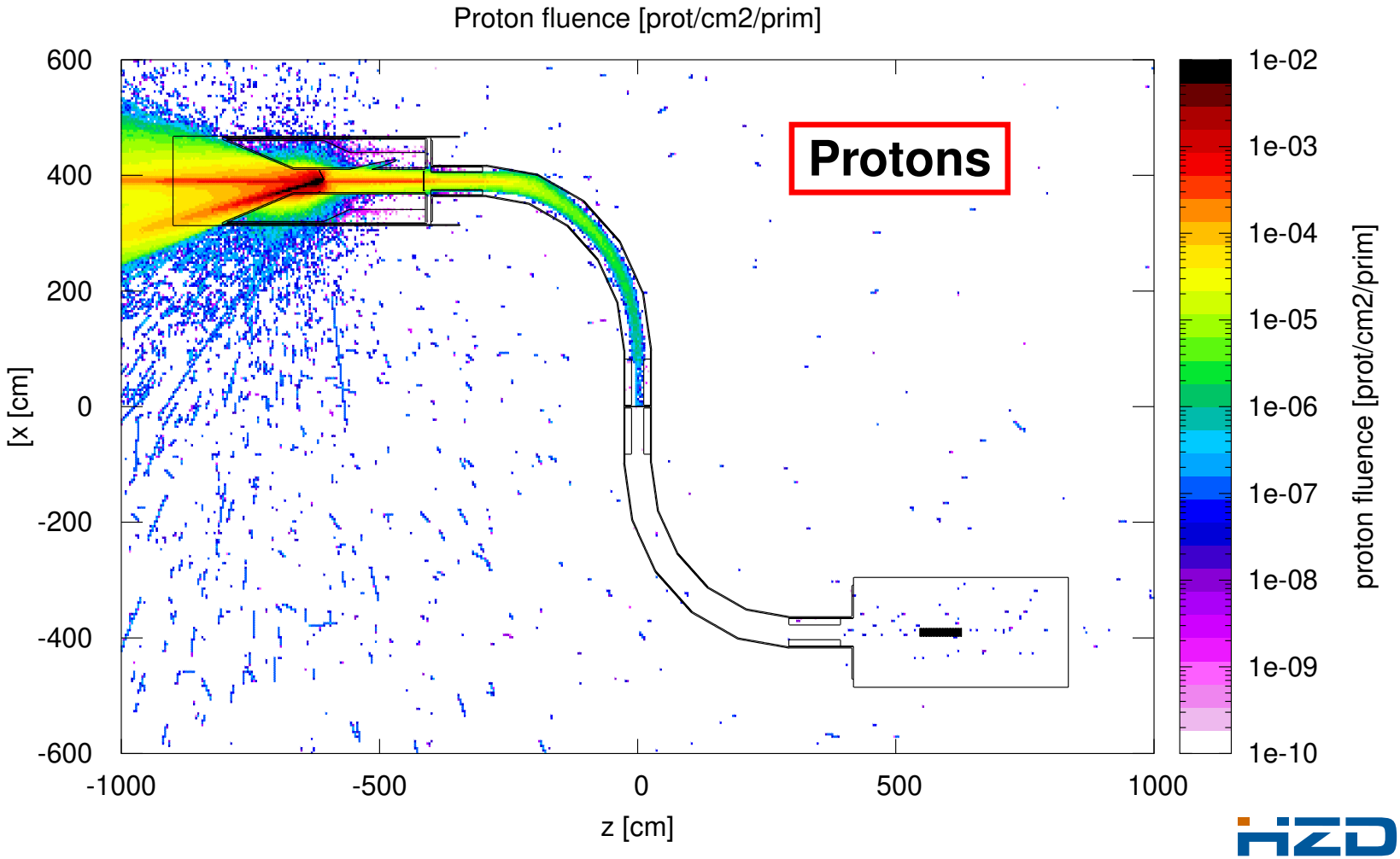

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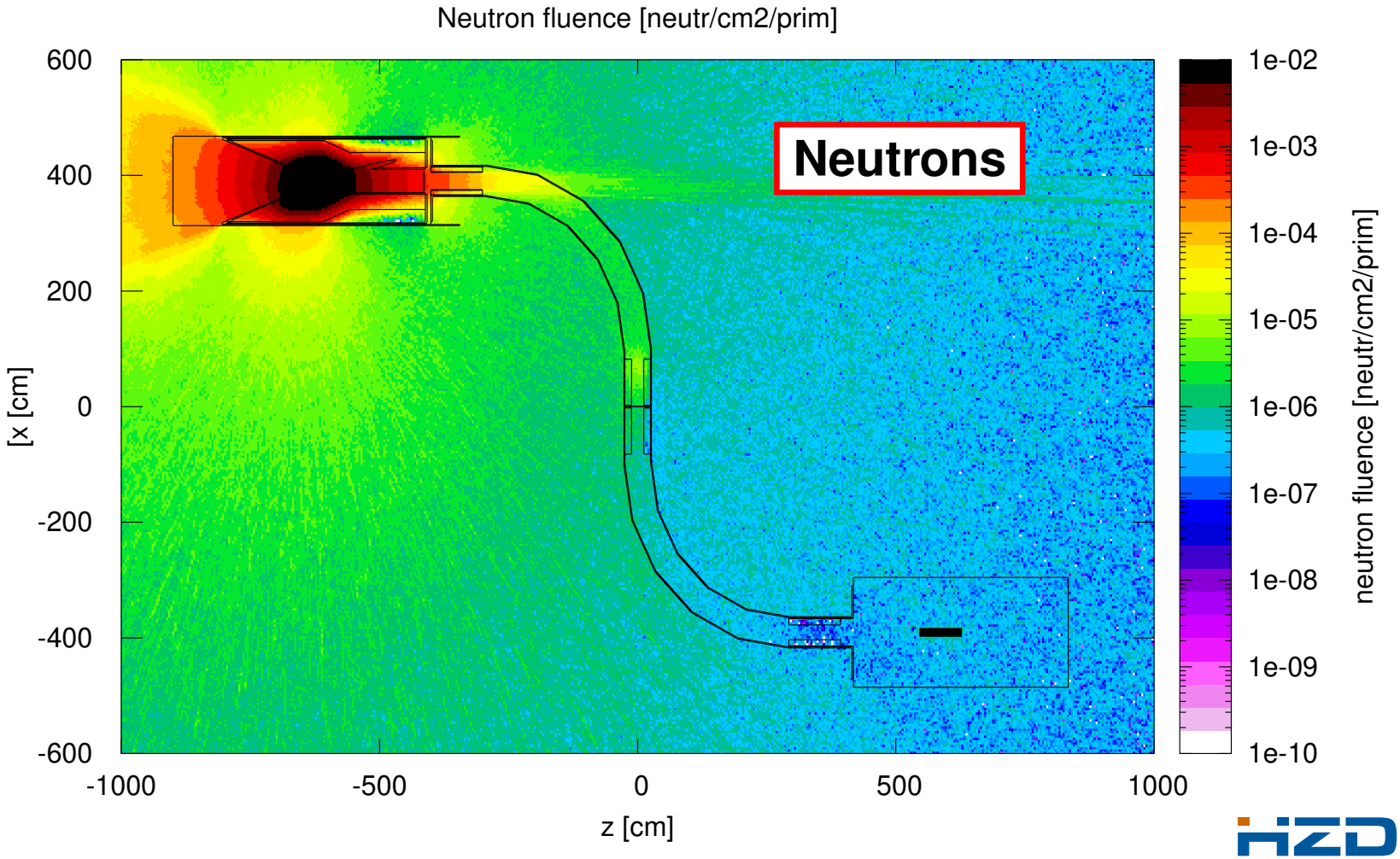
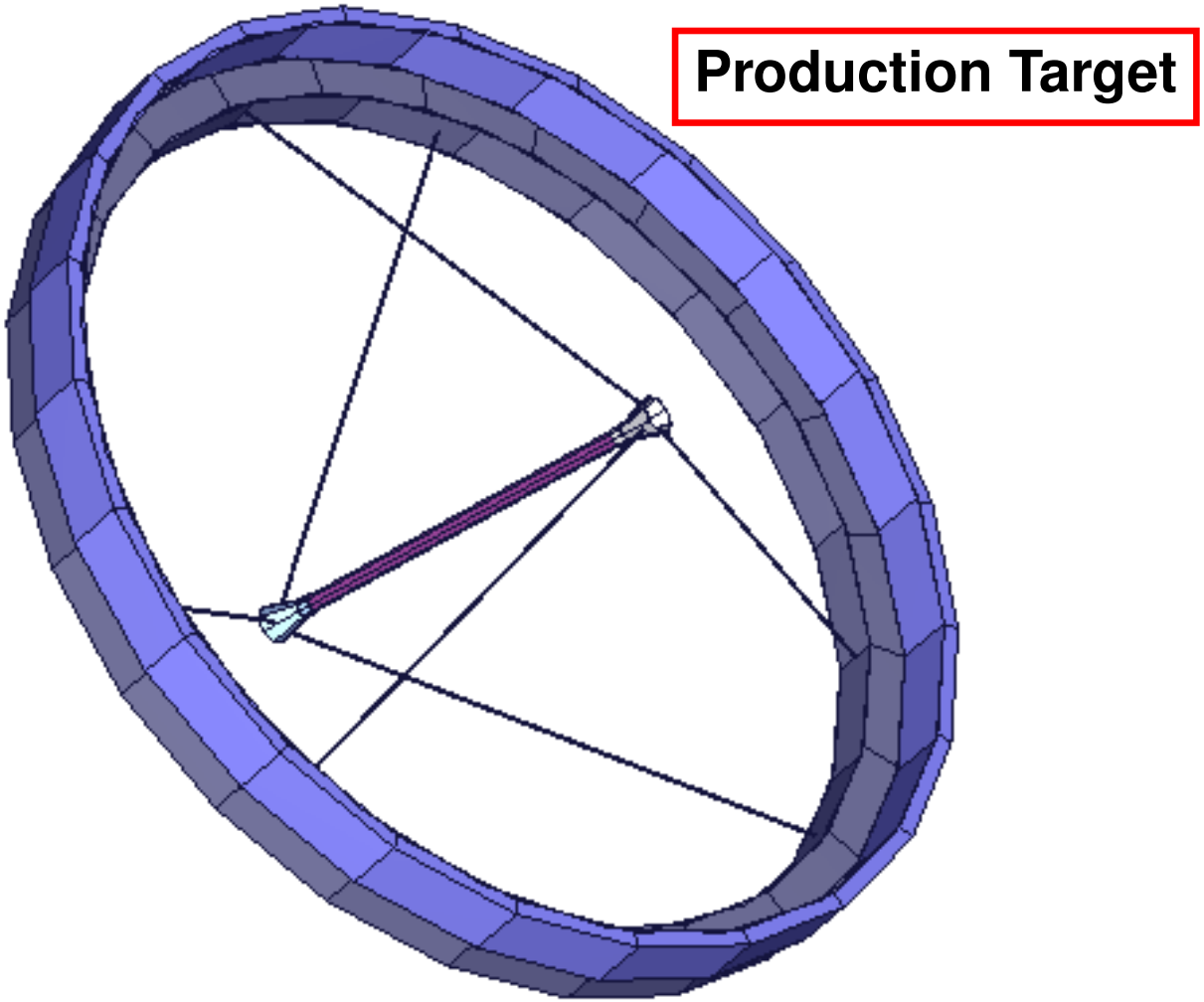


Next steps:

- Debug and optimize the present geometry
- Add scoring for each Virtual Detector region similar to docdb-8080
  - Particle yield entering VD: 900 bins in momentum from 0. - 9. GeV
  - Position of particle in transversal plane 500 bins for -25 cm < x_{trans}, y_{trans} < 25 cm
- stopped muons per POT
  - What is the best way?
- Continue with geometry:
  - Structures inside DS
  - STM
  - additional structures around PS
  - Shielding walls

MCNP activities at HZDR

Reuven Rachamin started to implement the Mu2e geometry into MCNP6 (using the existing FLUKA geometry)



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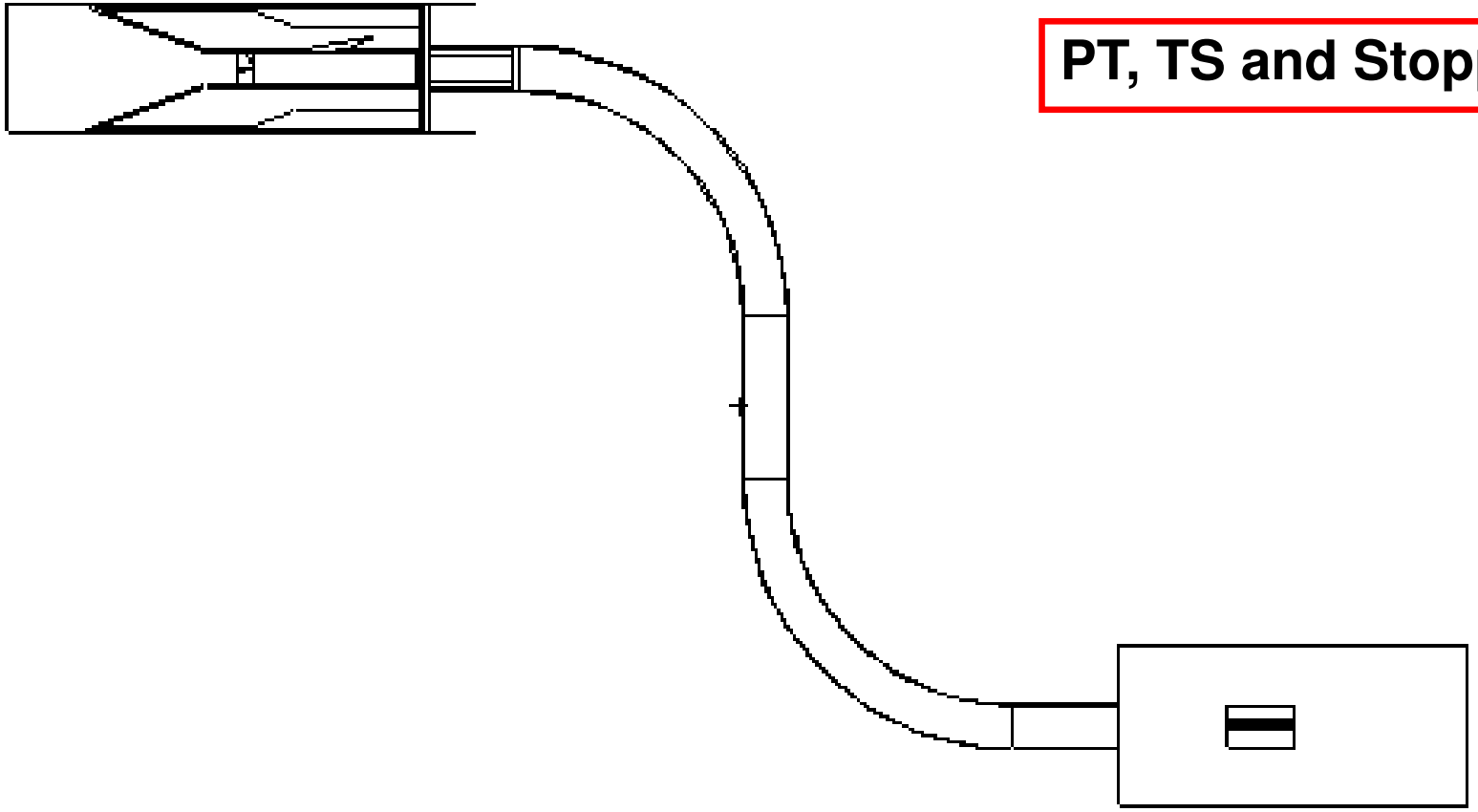


PT, TS and Stopping Target

MCNP activities at HZDR

Reuven Rachamin started to implement the Mu2e geometry into MCNP6 (using the existing FLUKA geometry)

- MCNP6 is reference code for (low energy) neutron transport
- Event generator for nuclear reactions: LAQGSM03.03 (Los Alamos Quark-Gluon-String-Model)
- Comparison of proton and neutron spectra exiting Production Target with MARS, FLUKA, etc.
- Goal: Shielding optimization
- Possibility to implement magnetic fieldmaps?

Summary and outlook

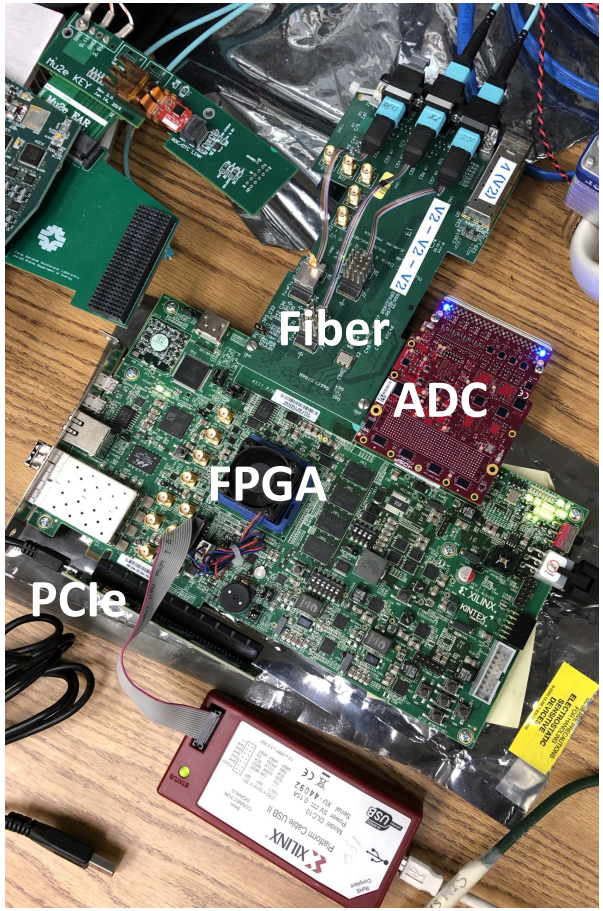
- Lot of work has been done to simulate the MU2E experiment using **FLUKA** radiation transport and reaction passage
- Several helper routines developed to transfer **GEANT4** volume description to **FLUKA** geometry description
- Method to read **Mu2e** fieldmaps in **G4Beamline** format into **FLUKA** has been developed
- PS and TS have been simulated, first simulations showing that muons arrive at the stopping target
- This allows to answer the questions asked by Doug Glenzinski
- Also started simulation activities using **MCNP6**
  - mainly for neutron shielding optimization studies

Oliver Knodel

STM-DAQ FPGA @ Feynman Computing Center

Idea:

- **Analyzing the detector data directly in hardware on the FPGA**
- Using HLS to optimize the design process and allowing a non-HDL FPGA "programming"
- "Everybody" can write own algorithms for the special low-latency hardware



Why High-Level-Synthesis (HLS)?

- Generate hardware cores from software (C/C++) based on Xilinx Vivado/SDAccel.
- Optimize the hardware design with separate implementation hints (`#pragma`).
- Application can be parallelized and compiled to a low-latency hardware/FPGA module.

First Results — Performance

- Clock: 200 MHz (5 ns).
- Number of total cycles for optimized simple example (DATASET 100), input buffer caching and a floating-point double multiplication can be simulated.
- The overall latency of the Pipeline is:

115 clock cycles

= 575 ns

(pure DAQ-IP-Core execution time on FPGA
On a data stream with pipelining)

- And the throughput?

Performance Estimates

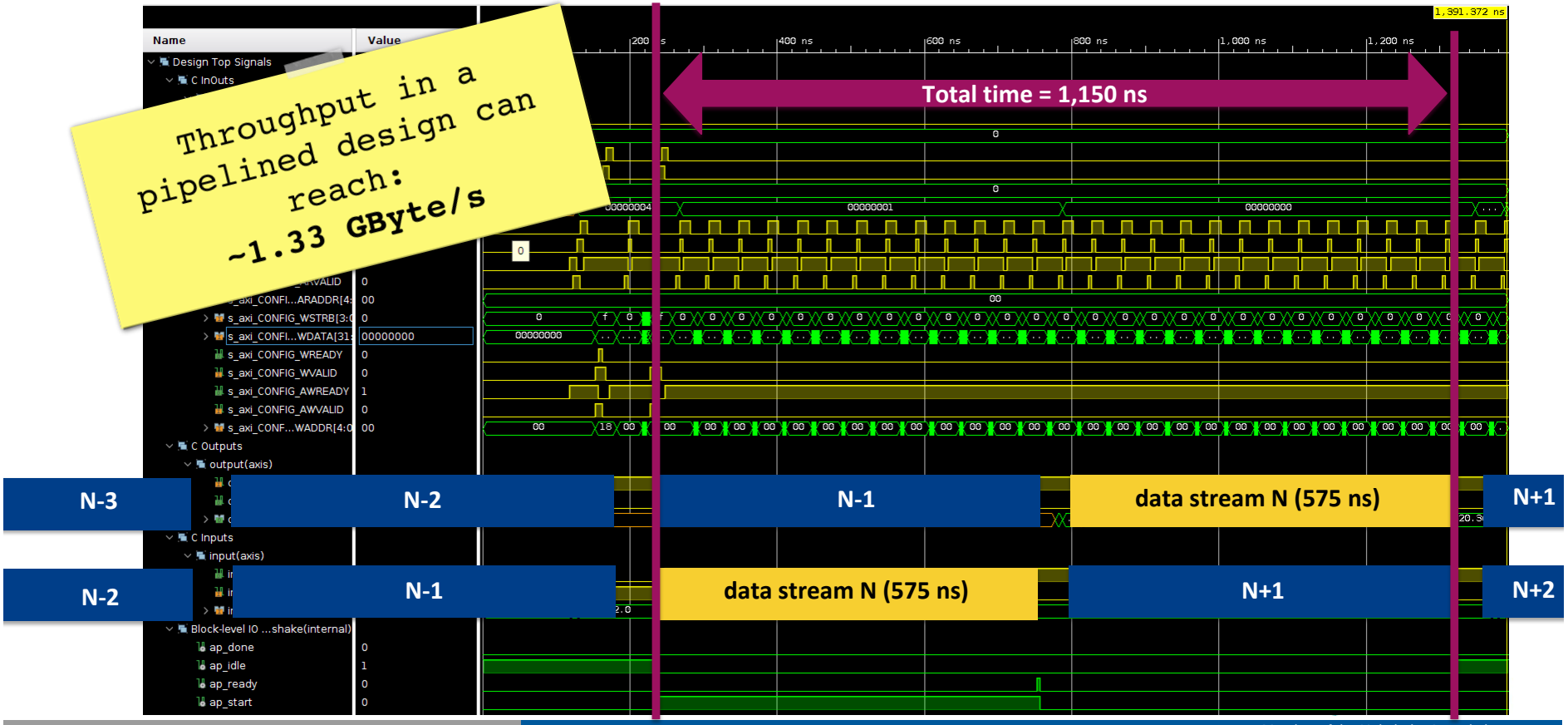
Timing (ns)

Clock		pipeline+unroll	dataflow	initial	pipeline
ap_clk	Target	5.00	5.00	5.00	5.00
	Estimated	4.375	4.375	4.140	4.375

Latency (clock cycles)

		pipeline+unroll	dataflow	initial	pipeline
Latency	min	115	1103	1403	115
	max	115	1103	1403	115
Interval	min	113	1103	1403	113
	max	113	1103	1403	113

Utilization Estimates

	pipeline+unroll	dataflow	initial	pipeline
BRAM_18K	356	356	0	356
DSP48E	11	11	11	11
FF	39668	39546	26704	39668
LUT	51213	51167	44622	51213
URAM	0	0	0	0

First Results — Theoretical Timing and Throughput